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DESIGN GUIDELINES FOR GOOD HEARING CONDITIONS AND EFFECTIVE NOISE CONTROL IN SCHOOL CLASSROOMS.

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TWO OF THE MOST IMPORTANT OPERATIVE DESIGN FACTORS GOVERNING SPEECH PERCEPTION IN CLASSROOMS HAVE BEEN EXAMINED AND GUIDELINES IN THE FORM OF GRAPHS, ETC. CONSTRUCTED THAT SHOULD BE UNDERSTANDABLE TO AND USABLE BY THOSE ASSOCIATED WITH SCHOOL PLANNING AND DESIGN. THE TWO FACTORS CONSIDERED ARE--(1) PROVISION FOR OPTIMUM REVERBERATION TIME, AND (2) PREDICTION OF SPEECH INTELLIGIBILITY (ARTICULATION) BY USE OF THE ARTICULATION INDEX. THE REQUIRED ADDITIONAL ACOUSTIC ABSORPTION TO PROVIDE OPTIMUM REVERBERATION TIMES IN A VARIETY OF CLASSROOM SIZES AND OCCUPANCIES IS SHOWN IN THE FORM OF GRAPHS. ARTICULATION INDEX IS A WEIGHTED FRACTION REPRESENTING, FOR GIVEN SPEECH AND NOISE CONDITIONS, THE EFFECTIVE PROPORTION OF THE NORMAL SPEECH SIGNAL AVAILABLE TO THE LISTENER FOR CONVEYING SPEECH INTELLIGIBILITY. CONSIDERED IN THE CALCULATIONS ARE THE NATURE OF THE SPEECH SPECTRUM, ATTENUATION OF THE SPEECH SIGNAL BEFORE REACHING THE EAR, AND THE EFFECTS OF NOISE IN MASKING THE SIGNAL. STARTING WITH KNOWN FACTS, AND ASSUMPTIONS, NOISE LEVEL LIMITS FOR EFFECTIVE SPEECH COMMUNICATION ARE DETERMINED FOR VARIOUS SPEAKER-LISTENER DISTANCES TYPICAL OF CLASSROOMS. USING THESE CALCULATED VALUES, GUIDELINES GRAPHS HAVE BEEN PREPARED WHICH SHOW WHAT SOUND TRANSMISSION LOSS PROPERTIES OF EXTERIOR AND INTERIOR WALLS ARE REQUIRED, FOR SEVERAL EXTERIOR NOISE CONDITIONS. CONSIDERATIONS ARE ALSO GIVEN FOR SOUND TRANSMISSION LOSS UNDER MAXIMUM NOISE LEVELS. (RK)

FINAL REPORT
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CONTENTS

INTRODUCTION

It is a sad fact that many school buildings are being designed currently without taking advantage of the acoustical knowledge available today. Visits to a large number of contemporary school buildings reveal frequently that the only attention paid to the whole art and science of architectural acoustics is to install large amounts of acoustical absorption material, often in the wrong places.

Schools and classrooms are becoming, inevitably, more noisy. The increasing urbanization of our population tends to create more noisy sites; additional mechanical and teaching equipment makes more noise inside; continually rising building costs necessitate more compact buildings and multiple usage spaces to stay within budgets.

While it is certain that we do not know all the important facts about the perception of speech in enclosed spaces in the presence of noise, it is also certain that we do know enough to make the design of school classrooms serve more effectively for teacher-student interactive speech communication.

It seems obvious that the stimuli received both through the eye and ear are necessary for information transfer in the classroom. Whether one is more important than the other might be debated. Yet it is interesting to compare what is available in planning or design documents, including codes, concerning the visual environment with what is available for the acoustical environment. The visual environment is frequently defined in terms of explicit design goals for illumination levels, brightness ratios, etc. Recommendations for the acoustical environment, on the other hand, are usually limited to platitudes about "acoustical balance" or "proper sound insulation of rooms". Seldom, if ever, have any numbers been used to describe the desired acoustical conditions.

OBJECTIVES

The primary objective of this study is to develop a set of systematic guidelines for the acoustical design of school classrooms. These guidelines or criteria deal mainly with adequate noise control in and between classrooms and good hearing conditions within these classrooms. The guidelines are presented in a form suitable for architects, engineers, and administrators who have a limited understanding of acoustics. A secondary objective is to accentuate problem areas in space planning, design, and construction materials and equipment that can cause difficulty in effective noise control or room acoustics. Another secondary objective is to emphasize the difference between effective noise control between spaces and good hearing conditions within spaces as an aid in reducing widely held misconceptions about acoustical control in school buildings.

The area of consideration in this study is limited entirely to direct speech communication in the secondary school classroom or other spaces where teacher-student interaction is of primary importance.

Two of the most important factors governing good hearing and effective noise control in the 'live' circumstance are reverberation time and speech articulation, as predicted by Articulation Index. This study uses these two operative factors as the basis for the development of design guidelines.

It is hoped that the results of this study will eventually become an integral part of the considerations required for school construction. These results are developed into a simple format in the form of graphs or charts.

PROCEDURE

Reverberation Time Studies. Reverberation time is the prolongation of sound after the source has stopped, caused by multiple reflections from the surfaces of the room. More technically, it is the time it takes the intensity of this sound to decay 60 decibels and is a function of the room volume and the amount of acoustical absorption contained within the room. It is an inherent property of all enclosed spaces, and as such, is not, per se, an acoustical "defect". Long reverberation times may be enjoyable for music, but not for speech, since the successive syllables will overlap, leading to difficulty in understanding. Very short reverberation times, on the other hand, lead to the perception of a space as being "dead" and occasionally somewhat unpleasant and require higher speech effort.

Optimum times for speech and other functions have been determined by experience and are available in numerous text references, such as Knudsen and Harris (1950), Beranek (1954). This study covers a range of room volumes which are typical of standard contemporary school design. The volumes selected for this study range from about 5000 cu ft to about 34,000 cu ft. The prime objective is to determine the amount of absorption that is required in any classroom within this volume range in order to achieve an optimum reverberation time. This phase may help correct the common misconception that the answer to classroom acoustics is to cover the entire ceiling with acoustical tile.

It can be shown that the optimum reverberation time for classrooms with volumes of 5,000 to 12,000 cu ft is 0.65 seconds $\pm$ 0.10. Since the range of reverberation times is so small for this range of volumes, it is assumed that the reverberation time is constant for these volumes and equals 0.65 seconds at 500 Hertz (Hz) or cps.

The actual reverberation time that exists in any enclosed space is a function of both the volume and the amount of acoustic absorption contained within the space. The absorption in a classroom consists of the occupants and the surface finishing materials, i.e., concrete block, acoustic tile, and glass. The volumes of 5,000 to 12,000 cu ft are equivalent to classrooms ranging in size from 600 sq ft with an 8 1/2 ft ceiling to 1000 sq ft rooms with a 12 ft ceiling. In a typical high school classroom with an occupancy of 25 to 35 students, the floor areas vary from about 650 to 900 sq ft. Using these values and a constant reverberation time of 0.65 seconds, the amount of absorption required in these spaces, in order to realize the optimum reverberation time, can be calculated. The ranges of these spaces are:

Occupancy	Room Area, sq ft	Ceiling Height, feet
25	650, 700, 750	9, 10, 11
30	650, 700, 750	9, 10, 11
35	650, 700, 750	9, 10, 11

In order to perform these calculations a set of parameters was established in order to develop hypothetical spaces which approximate the typical classroom situation; these parameters had to cover a wide range of possible classroom construction. The selection of materials was limited to those found in contemporary school design, i.e., concrete block, metal sandwich panels, plastic, glass. A very wide range of such materials is available on the market; however, by assuming only the acoustical properties of such materials, the range has been narrowed considerably, for the purpose of the study.

The development of a classroom of any volume has been broken down into three variable conditions:

(1) "Standard" materials. This means any material within the classroom that remains the same for any given volume, even though other variables might change. These materials are chalkboard, glass, and floors of asphalt tile. Carpeting will be considered simply as another absorption material.

(2) Ceiling. This is considered at its initial stage of construction, before any absorption material is applied. This variable is limited by using acoustical parameters to two possible conditions, these called either "hard" or "soft" ceilings. Hard and soft again refer to the acoustical parameters of the material, that is, hard material such as concrete or plaster which offers little sound absorption as opposed to soft ceilings of more flexible materials such as gypsum board which has somewhat higher absorption, but still far less than standard acoustical absorption materials. Therefore, hard can be considered as non-flexible material and soft as somewhat flexible.

(3) Wall material. Once again, using acoustical terminology, wall material is limited to three possibilities: (1) non-porous flexible surfaces, i.e. metal panels or dry wall construction, (2) non-porous

non-flexible surfaces, i.e. plaster, and (3) porous non-flexible surfaces, i.e. concrete block or similar material.

Another standard factor for any given area is the occupancy of the space. This occupancy is determined by optimum capacity of the classrooms of the mentioned volumes and floor areas. All acoustical values for these materials, that is, absorption coefficient, are taken either from well known sources such as Knudsen and Harris (1950) or averages taken from published manufacturers' data that cover the variable materials. Such materials as glass and chalkboard are assumed to be a certain percentage of the floor area. These percentages were, as in the case of glass, taken from averages of either contemporary school design or code requirements. Thus, the percentages arrived at were 15 percent of the floor area for glass and approximately 18 percent of the floor area for chalkboard. Using these parameters the calculations were performed by computer and tabulated in Table I. The values represent the average absorption required in the six possible situations. However, these averages are assumed to be sufficiently accurate since the total range of absorption varied only slightly as compared to the average.

The remainder of volumes in the study, those from 12,000 to 34,000 cu ft, by reason of their size, produce the more critical conditions that arise in large group instructional areas. They commonly seat 50-150 students and may take the form of a double classroom with movable wall to more formal lecture spaces. By reason of size variation, the optimum desired reverberation time can no longer be considered a constant and must be calculated for the different spaces. In this study these optimum times were calculated by the classic reverberation formula; $T_{60} = \frac{0.049\ V}{S\bar{\alpha}}$, where, V = volume, S = surface area of the room, and $\bar{\alpha}$ = the average acoustical absorption in the space.

The results obtained by this formula are indicated by the summary chart in the appendix for each of the spaces selected for this area; the spaces set up for calculation are indicated below:

Occupancy	Floor Area, sq ft	Ceiling Height, ft
50	1300, 1400, 1500	10, 11, 12
60	1400, 1500, 1600	10, 11, 12
70	1500, 1600, 1700	10, 11, 12
80	1000, 1100, 1200	10, 12, 14
100	1250, 1350, 1500	10, 12, 14
120	1500, 1600, 1800	10, 12, 14
140	1800, 1900, 2100	10, 12, 14
160	2000, 2200, 2400	10, 12, 14

Using these room sizes the same calculations were performed as for the smaller rooms, that is, the amount of absorption that must be added to the space to realize the optimum reverberation times. Again, due to the small variation of materials, the average absorption was computed and may be found also in Table I. The assumed values for walls, ceilings and floors are shown in Appendix I.

The first three of the above group of spaces, above the line, may be considered as double classrooms. Below the line are occupancies and floor areas that may be typical of large group instructional areas, with differing seating densities than in classrooms. The basis for calculating the areas corresponding to occupancy is 12.5, 13.5 and 15 sq ft per student. Since a common seating density for the formalized seating of an auditorium is 8-10 sq ft per person, these areas do not seem particularly restrictive.

Carpet is an excellent acoustical material that not only acts as absorption but also as a sound deadening material by stopping sound as its source. Carpet is becoming a popular material for use in classroom design since it offers both of these qualities. For this reason, carpet was incorporated into the study and considered as a separate material in the calculation because of its high absorptive qualities. The calculations involving carpet were performed in the same manner as the previous ones, except that the floor was considered to be completely covered with a heavy duty synthetic carpet. The absorption values for such carpets were taken from recently determined laboratory data (American Carpet Institute). However, assuming that the student and desks cover or "shadow" a large proportion of the floor, only 50 percent of the actual values were considered to be effective. This assumption has not been verified in actual installations. These values may be found in Table II, and the results of these calculations found in Chart II. One can see from these results that, due to the high absorptivity of carpet, very little additional absorption is required in classrooms to obtain optimum reverberation; in a few situations the carpet may even offer too much absorption and the space may approach a "dead" effect (denoted by the negative values).

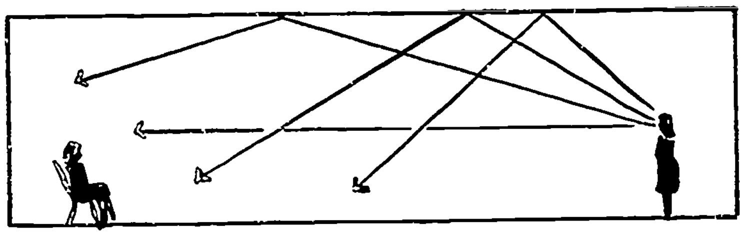
The calculations performed in the reverberation time portion of the study showed that the largest portion of absorption in a classroom is contributed by the students themselves. Therefore, consolidating these results so they may be easily understood, the governing factor in the following graphs is the occupancy of the spaces. These graphs represent the amount of additional absorption required in a typical classroom in square feet. The graphs are constructed for different NRC (Noise Reduction Coefficient) values, that is, for acoustically absorptive materials with different average absorptive coefficients. The U.S. Federal Specification (SS-A-118-9) is used as a standard for the NRC values which range from 0.35 to 0.90.

These graphs are simply constructed and should be quite easily understood by architect-engineers. The floor area of the classroom, in square feet, is plotted against the square feet of absorptive material required in the classroom in order to achieve the optimum reverberation time, while the height of the space is used as the objective function. Therefore, to use the graphs the architect only needs to know the size of the classroom, square feet, and height, and the expected occupancy; by selecting any acoustical absorptive material of his choosing, he may determine the amount of this absorption that is required. The graphs (Fig. 1, a-p) have a range of approximately 10 sq ft. This range allows for the placement of the materials, that is, the architects or engineers may allow variation due to the shape or size of the room or placement of mechanical equipment.

As mentioned previously, carpet offers a great deal of absorption; therefore, separate graphs (Fig. 2, a-d) are constructed for classrooms using carpet as floor covering; these are identical in character as those previously explained. One can see the great difference in absorption required in any one space by comparing two identical classrooms under similar conditions of these two sets of graphs. These graphs indicate the carpeting supplies enough, or more than enough, absorptive to meet the optimum reverberation time criterion, and that no additional absorption is required. This conclusion is correct but not desirable. Concentration of the absorption in a room on one surface, whether it be the floor or ceiling, is seldom desirable for optimum speech perception and acoustic comfort. Therefore, it is recommended, in spite of the absorption supplied by the carpet, that about 25% of the ceiling area be covered with absorption, and this area be around the perimeter of the ceiling.

From these graphs the architect-engineer may obtain sufficient information as to the amount of absorption required in any one particular classroom. However, the placement of this material requires some understanding of the properties of sound in order to perform properly. Perhaps the most important rule to remember in the placing of acoustical absorptive material is never to place it on a surface that may be useful for sound reflection, that is, any surface between the speaker and the listener which will reflect the direct sound of the speaker toward the listener or to the rear of the room.

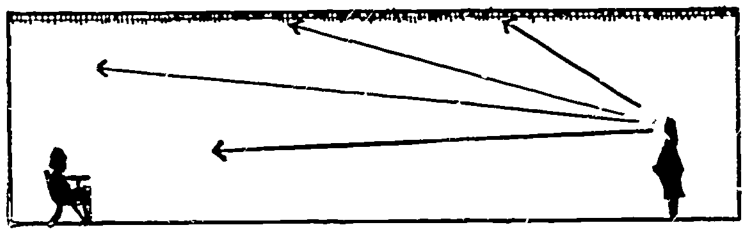
Sound Reflected



Sketch (a)

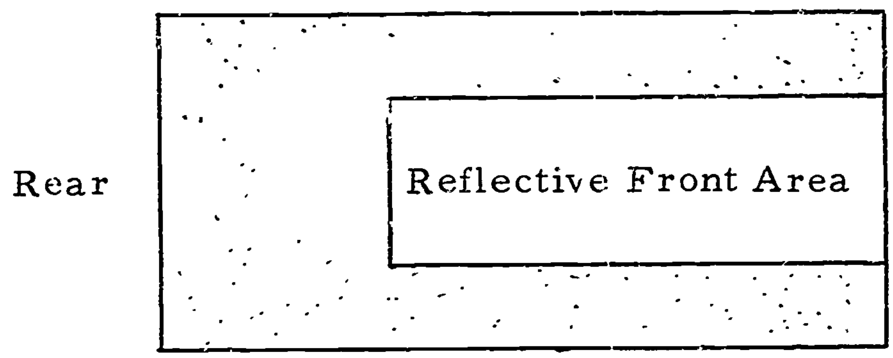
As shown in the above sketch (a), sound waves can be considered to be similar to light and may be represented by straight-line rays, where the angle of incidence is equal to the angle of reflection. One can see in the sketch that a hard reflective ceiling can greatly increase the amount of sound that reaches the listener. If the ceiling were covered with acoustical tile or other absorption materials, a large percentage of sound would be absorbed before it could reach the rear of the room (as in sketch (b)) and only the direct sound from the speaker would be useful. In small rooms where the distance from the speaker to the listener is not more than about fifteen feet, this direct sound would be sufficient for good hearing; however, the average classroom dimensions are much greater than this and the reflective sound is an aid to good hearing conditions. Therefore, it is essential that the placement of acoustical absorption not interfere with these needed reflections.

Sound Absorptive Materials



Sketch (b)

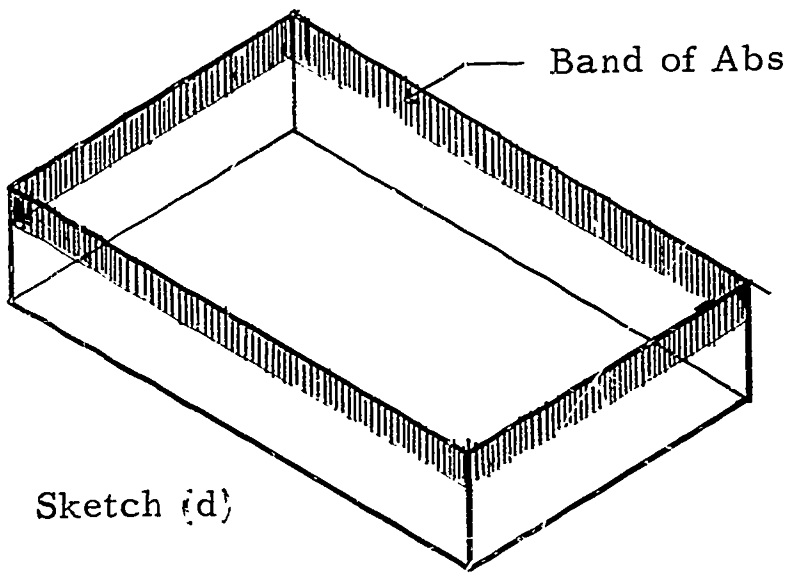
From this one can conclude that the ceiling of a classroom, especially the center section, is not the surface to use as area for absorption placement. The area along the edges or especially at the rear of the room offers little reflection of desired sound; therefore, these areas logically seem more suitable for the placement of absorption, as shown in the ceiling plan below.



Reflected Ceiling Plan

Sketch (c)

Because the majority of classrooms have ceiling heights of 9 to 14 ft, a large area of useful surface area is available for the placement of absorption; however, since most acoustical absorptive material is susceptible to damage, the material should not be placed within reach of the occupants. Assuming that about eight feet is a minimum limit for this height, there still exists a band of area from one to six feet around most classrooms which offers additional space for absorption placement. Allowing these possibilities for placement of absorption (i.e., the edges of the ceiling, except the front, and the band of wall area below the ceiling), a sufficient amount of surface area exists for absorption to obtain the optimum reverberation time in any typical classroom.



Sketch (d)

Articulation Index Studies. The most valid procedure for measuring the ability of a communication system to transmit intelligible speech is to subject that system to a series of intelligibility tests. However, this is an expensive and time consuming procedure, requiring trained speakers and listeners, as well as having the actual system available for tests. Obviously, in the design stage of a classroom the physical system is not yet available for these tests. If one were to wait for the system to be constructed, little value could be obtained by making acoustical corrections after the classroom was already built. Therefore, the primary objective of this section is to develop guidelines that will be useful during the design stage in obtaining the highest percentage of intelligible speech in any classroom.

Methods have been developed for calculating from acoustical measurements and estimates a measure that correlates highly with the intelligibility of speech as evaluated by speech perception tests. This measure is called the

Articulation Index (AI). It is a weighted fraction representing, for given speech and noise conditions, the effective proportion of the normal speech signal which is available to a listener for conveying speech intelligibility. This method of calculating speech intelligibility has been used for quite some time in "closed" systems, that is, electronic communication systems, such as telephones and public address systems; however, very little has been done in the way of the "live" situation, or the direct communication between speaker and listener in rooms.

In the communication system the starting point is the speech spectrum, i.e., the sound level measured in decibels (subjectively called loudness) over the range of frequencies of speech. Since many high school teachers are female, it would seem logical to use the female speech spectrum for the calculation of AI in the typical classrooms. Also, since the female voice is usually softer than the male voice, this would offer the lowest usual speech spectrum level that would produce the minimum solution which, in turn, would be of the greatest value to this study. However, the AI has not yet been validated for anything but male voices (Kryter, 1962) and furthermore, the spectrum used in Kryter's method is idealized: it is not necessarily the actual speech spectrum for a number of speakers. Little has been done in the way of female spectrum level. Fletcher (1953) has compared the power of female to male voices. Using Fletcher's curves and the male spectrum after Beranek (1954) (see Fig. 3) and superimposing these two curves, a spectrum level was derived that represents the minimum values of the two curves. Comparing these values to the Kryter curve the results indicate that the assumed values are an average 2-4 dB lower than Kryter's values, and since it is generally accepted that the female voice is 3-5 dB less powerful than the male voices this assumption is considered valid. Further comparison of these values will be indicated later on when considering the final solutions.

The second governing factor in the calculation of AI in a room is the distance between source and listener, and closely related to this is the absorption characteristics of the space between the speaker and listener. Once again little research has been done on the variation of sound pressure in rooms similar to classrooms. Material available is actually only valid in large irregularly shaped rooms; in these spaces the sound pressure varies very little after reaching some distance from the source where the reverberant characteristics of the space have greater influence than the direct sound. This may be seen by the upper curve of Fig. 4. The change in sound pressure is a function of the total absorption in the space which is represented by the Room Constant (R), on the right ordinate of the graph. The room constant expresses the average absorption in a space relative to the surface area of the space:

$R = \frac{S\bar{\alpha}}{1-\bar{\alpha}}$, where; S = surface area - sq ft and $\bar{\alpha}$ is the average absorption coefficient of the space. However, a typical low ceiling classroom is not a "large, irregularly shaped" enclosure. From the limited material available there is an indication that for spaces with absorption on both the floor and ceiling of wide, flat spaces (Gober, 1966), the variation of sound level with distance approaches the free field situation, which is a drop of 6 dB per doubling of distance, represented by the bottom curve of Fig. 4. For classrooms with limited absorption that approach the optimum reverberation time, it is believed that the curve which would indicate the actual variation in sound pressure level due to distance lies somewhere between the two indicated on the graph. The actual curve would follow the free field situation until the direct and reverberant field became equal; then the level would decrease at a rate of 3.5 to 4.5 dB per doubling of distance. However, time and facilities were not available to verify these assumptions by actual tests; hence the calculations were performed using the situation applicable to the large, irregularly shaped space. It is hoped that sometime these assumptions will be validated and corrections made.

It is assumed, in relation to distance, that the listener, or student, is in the most distant and noisiest position in the classroom. Given today's usual classroom heating and ventilating systems, the noisiest position probably is that closest to the air outlet, which may not be the most distant. Nonetheless, the described case is a limiting condition and any improvement can only result in improved intelligibility in teacher-pupil interaction.

The final governing factor in the calculation of AI is the noise in the system. This may be composed of noise from the next classroom, from exterior sources, or from the mechanical equipment or occupants within the room. The calculations were first performed considering only the internal noise, mainly that of air handling systems, and then the effect on these results by the possible addition of exterior noise was considered.

AI calculations for this study were performed for the various classroom sizes and occupancies listed in the section on reverberation studies so that these may be correlated in order to obtain useful results. The calculations were performed under the following assumptions:

1. The speaker is at the front of the classroom, speaking in a normal voice.

   (a) Teacher speaking in a raised voice.

2. The most critical listening position is at the rear of the classroom, where the most distant student is sitting.

3. The desired AI is 0.70, which corresponds to an understanding of 90 percent or greater of phonetically balanced words, and 99 percent plus for sentences with which the listener is familiar (see Fig. 5).

The conditions under which these assumptions were considered are:

1. No noise from adjacent spaces or exterior and,

   (a) A "quiet" ventilating system - NC-25.
   (b) A "moderately noisy" ventilating system - NC-35.
   (c) A "noisy" ventilating system - NC-45.

These NC values or numerical definition of quiet to noisy are as defined in Chapter 31, American Society of Heating, Refrigerating and Air-Conditioning Engineers Guide (1967). They are continuous spectrum noises and are typical of the noise created by many air handling systems used in schools. The typical form of these contours is shown in Fig. 9 These conditions represent the idealized conditions in a school classroom, in that it is acoustically separated from the remainder of the spaces in the school. These conditions may be approached and indeed realized where there is a high degree of acoustic isolation between adjacent classrooms and where low exterior noise levels exist. Using these calculations as a base, the effect of changing exterior and interior noise levels on the AI are shown, including such changes as rural vs. urban school sites with their concomitant exterior noise conditions, as well as light vs. heavy exterior wall construction and varying noise levels intruding from adjacent spaces.

The method of calculating the AI for any space followed very closely that of Kryter's validated method, but using the assumption that the female voice is at the minimum levels shown in Fig. 3. There are several methods used in the calculation of AI. The first method, after French and Steinberg (1949), uses the 20-Band method, that is, the speech spectrum is divided into 20 frequency bands, each contributing equally to speech intelligibility. There are three other methods used that have been derived from the 20-Band system: (1) the 1/3 octave-band method, (2) the octave-band methods, using either the 5 ASA preferred frequency bands, or (3) the 6 commercial filter bands. Of these methods the 20-Band and the 1/3 octave-band methods are the most accurate because they cover the speech and noise spectrums with narrow band widths and detect any particularly concentrated sounds. However, since this study uses estimated noise levels and not actual levels, the 6-Band method was selected for the calculation of AI. All the methods provide almost identical answers under similar conditions when the acoustical values are estimated and are not actual measurements; therefore, the 6-Band method should provide answers of sufficient accuracy for the purpose of this study.

As mentioned previously the (1) first step involved in the calculation of AI is the speech spectrum. Since the values used in the study for this have not been validated, the table in Appendix II compares the values of the assumed spectrum and the validated spectrum by Kryter. The resulting solutions are almost equivalent in value and, therefore, the assumed spectrum is considered valid for use in this study. (2) The second step is then to determine the reduction in sound pressure level due to distance. As stated earlier, this reduction has not been validated for small regular shaped rooms; therefore, for the purpose of this study the reduction in large irregular shaped rooms is used for the calculations. These reductions can be found on chart (3). This reduction in sound pressure level is dependent upon the distance from the speaker and the absorption characteristics of the space. The absorption present in a room is represented by the Room Constant (R), which is the ratio of the average absorption in the room to the total surface area of the room, $R = \frac{S\bar{\alpha}}{1-\bar{\alpha}}$, where, S = surface area in square feet, $\bar{\alpha}$ = average absorption coefficient for the room. Another factor in determining this reduction from the graph is the directivity factor of the source or teacher. It is apparent that the human voice is somewhat directional, that is, that at higher frequencies the voice tends to be more powerful in the direction in which the speaker is facing; depending upon the location of the speaker this trend toward directionality may be increased. If the speaker is standing with his back to a wall his speech power will be increased due to the reflections of the sound waves off the wall (the directivity of the speaker's voice has been increased due to the reinforcing effect of the reflections.) Assuming that a teacher in a classroom usually stands at the front center of the classroom facing the students, the directivity factor is considered equal to a value of two ($Q = 2$), i.e. hemispherical radiation. This value may be considered minimal since, as stated above, the human voice tends to be directional; therefore, the actual Q value may at times approach four (4). However, assuming the teacher may be facing the blackboard an undetermined amount of the time, the directivity of the voice is of no value, but the reflective reinforcement is still present and the Q value still equals two.

The next step (3) after subtracting the relative reduction from the spectrum level for each of the six bands is to add an additional 12 dB to this result. This 12 dB is equal to the maximum value of the speech peaks, i.e., 12 dB higher than the average speech spectrum values used in the first step. Step four (4) is then to simply subtract the noise present in the space from the value found in step 3. This value is the background noise either present or, as in the study, that which is due to the air handling equipment or external noise sources. To obtain the noise for the six different frequency bands, the values for the NC contours are used and, as stated previously, the initial calculations are concerned with NC levels of 25, 35, and 45, which may correspond to typical air handling systems. The resulting solutions can be seen in tabulated form in Tables 2, 3 and 4; these tables also indicate the difference between AI values for both normal and raised voice levels. These operations are also highly repetitive and were likewise handled by computer. The format of the calculations is shown in Appendix II.

The minimum acceptable AI value is assumed to be 0.7. This value for AI corresponds with an understanding of 90% for phonetically balanced word lists, and 99+% for sentences with which the listener is familiar. Lower values for the desired AI have been used in other work. For example, certain defense communication requirements have used the value of .50.

We believe the use of .70 is justified on the basis of wanting the students to understand the words in a sentence, as well as the sentence itself, and represents a reasonable compromise between barely understanding sentences at about .40 and the obviously desirable "perfect" understanding at 1.0.

From the tables one can see that this minimum is maintained for raised voice for most classrooms as long as the noise level is NC-35 or below; for normal voice this noise level is acceptable only for rooms up to approximately 15,000 cubic feet. In Fig. 6a and b, the AI is plotted against the volume of the classrooms, and the curves represent the NC - levels which would be acceptable for any particular AI desired. These two graphs should be of great value in the design phase of a classroom since they essentially recommend a minimum NC level for any volume classroom. However, they are valid only if the classroom is at its optimum reverberation time which could be determined from the graphs suggesting optimum absorption (Figs. 1 and 2). It is suggested that if these two sets of graphs, recommended absorption and recommended NC levels, are used during the preliminary design of any classroom, the resulting space would be much more conducive to good hearing conditions.

The preceding was primarily concerned with idealized conditions, that is, no external noise sources have been considered thus far. Assuming standard exterior wall types for typical schools, such as brick on concrete block or prefab metal panels with an average of 15 percent glass area, the average sound insulation value is about TL-30-35. TL refers to "transmission loss", which is equal to the number of decibels by which sound energy incident on a wall is reduced in transmission through it. Simply, if a particular wall has a TL = 30 and a noise source of one side of the wall is 60 dB, the resultant level on the opposite side of the wall will equal 30 dB, that is, it transmits 1/1,000 of the sound power incident on the wall. One can readily see that if the exterior noise level increases, the noise level that penetrates the wall will also increase if the TL of the wall remains constant. Realizing this, one can then assume that as the exterior noise increases, the background noise level in the classroom will also increase and, therefore, the resultant AI will decrease due to the increase of the noise in the system.

Tables 3 and 4 show the variations in calculated AI as the exterior noise level increases for a typical exterior wall with a TL of 30 dB. These increases are equated to the increase in noise level due to the relative location of a school. For example, in a rural area where the school is somewhat isolated from heavy traffic or other noise sources, the exterior noise level is assumed to be equivalent to NC levels of between NC-40-45. At these levels the AI is not affected to any extent. However, as the noise level increases to a level equal to that found in an urban area where heavy traffic is in close proximity of the school, this being equivalent to an NC-80$\pm$, the AI values decrease at a much more rapid rate. By equating the noise that penetrates an exterior wall to NC levels, one can see that for a typical urban classroom wall with a TL of 30, the noise coming through the wall is about equal to a background noise of NC-50 (80-30). By referring to Fig. 6, a and b, it is obvious that with a noise level equal to NC-50, even with a raised voice the minimum AI of 0.7 cannot be obtained. Therefore, if a school were built in an urban area, the sound insulative properties of the exterior wall must be higher than those common to standard school construction. Since the walls considered as typical were 15 percent glass, and since thin, single glass has a low TL value and therefore detracts from the entire wall, it would seem logical to reduce the area of glass in the exterior wall if a satisfactory AI is to be obtained. This can be more readily understood by the following example.

Assumptions:

1. Classroom with desired NC-30.
2. Interior partitions TL-45.
3. Urban conditions - equivalent to NC-80.

Assuming the TL 45 partition is sufficient to isolate any noise from neighboring classrooms, what exterior partition would be required?

Souce = 80 - TL wall = NC-30
TL = 50

To obtain a TL of 50 for a typical wall of 6-inch concrete block and 4-inch brick, an area of 0.3 percent may be glazed with 1/8-inch glass, which has a TL of 25. Therefore, to achieve effective noise control with standard construction in an urban area, only 0.3 percent of the exterior wall may be used for glass, e.g. in a typical 30 x 40 foot classroom with a 10 foot ceiling, only 1.2 square feet of glass can be used on the exterior 40 foot wall in order to maintain an NC-30 and an effective AI of 0.7.

On the opposite scale, the following example assumes the same conditions, except that the school is located in a rural area where the exterior noise is equivalent to an NC-40.

$$\text{Source} = 40 - \text{TL wall} = \text{NC-30}$$
$$\text{TL} = 10$$

One can see that all that is required for this situation is an exterior wall with a TL = 10. An all glass exterior wall would be acceptable.

These two simple examples point out the great effect on hearing and noise control when the exterior noise levels vary over a large range. Therefore, it is obvious that construction of an exterior wall for a typical classroom should be governed by its location relative to exterior noise sources, rather than as a fixed, stated percentage glass area. Figs. 7, a-c show the relationship between exterior noise level and allowable percentage of single glazing for walls having sound transmission losses of from 30 (light construction), to 55 (heavy construction). It is evident that if a school is to be built in an urban area or an area where heavy road or air traffic is present, the construction of the exterior wall must have a limited glass area, or the glass itself must be increased in its sound insulative properties. The glass would have to be heavy plate glass or double glazing to increase the effectiveness of the wall and would, in any event, have to be fixed in order to maintain the insulation required. Such heavy, fixed glass could increase the acceptable area possibly to 15-20 percent of the wall area, which would meet a majority of present code requirements. The same methodology and logic apply to holes in the exterior wall, such as for unit ventilators. The TL across a unit ventilator is seldom more than about 25 dB, and consequently their application is questionable in high noise environments.

Similar conditions arise with respect to interior partitions and their sound insulative properties. To insure the best hearing conditions in a classroom, the partitions separating classrooms must have sufficient transmission loss to maintain the desired noise level in any one of the classrooms. In situations where the student in one classroom is sitting on the opposite side of a wall from another teacher, the isolation of the wall is critical in order to achieve a minimum AI. Of course, the optimum situation would be to have no intelligible sound penetrating the partitions (the AI through the wall is equal to zero). However, with the trend toward lighter weight materials and open plans this is not easily accomplished. The intelligibility of penetrating sounds is sufficiently low when the AI is 0.04 or below based on ratings established for office partitions (Cavanaugh, Farrell, Hirtle, Watters (1962); therefore, the 0.04 value is considered the maximum percent of intelligible speech coming through a partition to maintain optimum conditions. This, again, can probably be more easily understood by referring to Fig. 8. This graph indicates what Sound Transmission Class (STC)* partition is required to achieve different AI values, depending upon the noise criterion (NC) of the receiving classroom. Simply, if the NC level of the receiving classroom is NC-30, then to achieve zero intelligibility of speech from the next classroom, the separating partition must be at least STC-45. STC-45 can be obtained by a number of constructions, including both movable and operable walls.

This STC-45 compares with an STC-25-30 which has been found acceptable in some schools, for example Lane (1957). However, "acceptable" does not necessarily mean "desirable", and at the high school level, the compatible functions of adjacent spaces may not occur as frequently as they do in elementary schools. Thus STC-45 seems a reasonable design goal for the classroom noise recommendations made in this report, which may be lowered as more is learned about desirable vs. acceptable in terms of students. Obviously, students and teachers will tolerate more intruding noise than, say, office workers, but tolerance should not necessarily be equated with performance.

*STC (Sound Transmission Class) is a preferred single number method of ranking the sound transmission loss characteristics of partition. It is defined in ASTM E-90-66T (1966) and is limited to speech type sounds through interior partitions. Average Transmission Loss (TL) values continue to be applied to exterior walls.

EXISTING CLASSROOM STUDY

Until this point, the emphasis has been upon hypothetical situations, that is, considerations needed in the design stages of a classroom. Now, a look will be taken at schools already functioning and how they compare with the ideal situations developed in this study.

Classroom data are from an EFL report by Fitzroy and Reid (1963) on the acoustical characteristics of schools located throughout the United States. The schools included have been rated as "acceptable" or higher by teachers and administrators. The following data from their report on high school classrooms are used:

1. Classroom sizes and volumes.

2. Reverberation times.

3. Classroom background noise.

4. Where available, the noise measurements on the ventilating system.

One assumption that has been made is that the occupancy of these classrooms is 30 students.

Using the data and assumption, the AI between teacher and student is calculated, with the assumed speaker-listener relationship of front to back of classroom.

Calculations of AI are also performed to show the AI at the student's ear from a teacher speaking in the adjacent classroom. These latter calculations essentially duplicate the calculations by Fitzroy and Reid, but the purpose is to show the effect of small changes in background noise in the space or in the noise reduction between classrooms. This is a speech privacy calculation. A large percentage of these classrooms are of the open plan type, which seem to be functioning adequately. Assuming two classes in session with one space, the AI will be calculated for the speech from a teacher in front of the class reaching a student in the second. The following are the results of these calculations for the classrooms indicated.

3/EC

A divisible classroom - 60 x 30 feet, two 30 student classes separated by a folding partition.

(a) Existing conditions: (one-half space)
Volume = 8100 cu ft, R = 580 sq ft
Reverberation time = 1.05 seconds (opt. 0.66)
Class silent = NC-47
AI between classrooms = 0.01

(b) Calculated:
Single class = AI at 30 feet = 0.46
Double class = AI at 60 feet = 0.24

(c) Recommendations:
If background noise was lowered to NC-40, AI would be acceptable at 0.71 for the single class, and 0.58 with double class.

STC value of partition not given; therefore, AI between classrooms not calculatable.

3/MW

A double classroom - 48 x 32 feet, two 30 student classes separated by folding partition.

(a) Existing conditions: (one-half space)
Volume = 7300 cu ft, R = 1300 sq ft
Reverberation time = 0.47 seconds (opt. 0.64)
Class silent = NC-42
AI between classrooms = 0.02

(b) Calculated:
Single class = AI = 0.48

(c) Recommendations:
If background noise was lowered to NC-35, the resulting AI would equal 0.72; however, if the reverberation time was at the optimum of 0.64 seconds, the NC could be 37, and the acceptable AI could still be achieved.

5/MW

Single classroom - 28 ft 6 in. x 31 ft - single class of 30 students.

(a) Existing conditions:
Volume = 8210 cu ft, R = 1180 sq ft
Reverberation time = 0.57 seconds (opt. 0.67)
Class silent = NC-47
AI between classrooms = 0.01

(b) Calculated:
AI = 0.39

(c) Recommendations:
If NC was lowered to 35; AI = 0.76, and the AI between classrooms will still remain below 0.01.

1/MW

Single classroom - 50 x 30 feet, 2 classes of 30 students, partially divided by a fixed glass partition.

(a) Existing conditions:
Volume = 15,500 cu ft, R = 815 sq ft
Reverberation time = 1.68 seconds (opt. 0.68)
Class silent = NC-43

(b) Calculated:
AI = 0.52

(c) Recommendations:
If NC were lowered to 35, AI = 0.77
The prime source of background noise for this classroom was the unit heater which produced an NC-40 with classroom empty.

AI between classrooms with NC-35 is still acceptable at less than 0.01.

4/MW

Single classroom - 37 ft 6 in. x 34 ft, class of 30 students. Classroom separated by movable partitions of STC-29.

(a) Existing conditions:

Volume = 10,764 cu ft, R = 720 sq ft
Reverberation time = 1.13 seconds (opt. 0.71)
Class silent = NC-51
AI between classrooms = 0.01

(b) Calculated:

AI = 0.32

(c) Recommendations:

If NC was lowered to NC-38, the AI would equal 0.70, however, due to the low STC of the partitions the AI between classrooms would be 0.09. If the partition had an STC-32 value, the AI between classrooms could be lowered to a value of 0.04, which may be considered acceptable. However, if a value of 0.01 is desired, the STC would have to be increased to STC-33, which is only a very slight increase.

From the preceding examples, one can see that the majority of schools have very low Articulation Index due to the high background noise. It is obvious that most of this noise is generated by the ventilation systems. One can also see that in most cases only a small change in background noise is required to produce satisfactory AI values, a change of the order of 5 dB. The AI between classroom values are all well under the minimum requirements; however, this is primarily due to the background noise masking any intruding speech. These values usually remain within the desired values when the background noise is lowered to a more desirable level. In situations where this change raises the AI between classrooms above recommended, the insulative characteristics of the partitions must be increased; however, this increase is usually minor, as pointed out in the examples.

It is interesting that most of the schools noted in the Fitzroy and Reid report are reported as being in the acceptable to satisfactory range. Two points may be made from this. The first is that human acoustic tolerance limits for speech perception are quite broad. The second is to ask if truly effective speech communication occurs in school rooms with high noise levels. It is true that the human ear, as part of a signal processing system, can effectively perceive speech in high noise environments, but it is likewise true that to do so requires a high order of concentration and motivation. Whether students can be continuously motivated seems questionable. It also seems questionable to require teachers to use the vocal effort necessary to be heard effectively in high noise environments.

EXAMPLE DESIGN

From the charts and graphs included in this report, it is possible for an architect or engineer to acoustically design a typical classroom. Assuming a standard single classroom with 30 by 45 foot dimensions, and an 11 foot ceiling height, the following indicates how such a room could be designed if the room is constructed with standard concrete block and the exterior wall is brick faced. How much sound absorption should be placed in the space? If an exterior noise level is equivalent to NC-65, is the exterior wall sufficient to maintain the desired NC-35? Assuming an occupancy of 60 students, determine if the AI is at an acceptable level.

First, from Fig. 1f, for an occupancy of 50-70, determine the square feet of NRC 0.80 acoustical tile needed. From the graph, 775 square feet of tile are required for a classroom of 1350 square feet and an eleven foot ceiling. Next go to Fig. 6a and b to decide if the AI for this space is acceptable. From Fig. 6a, one can see that for a normal voice level for a volume of 14,850 cu ft, the AI is just minimumly acceptable. However, from Fig. 6b for raised voices, the AI is acceptable at 0.74; therefore, the selected NC-35 is acceptable in this space if it can be maintained. A standard brick and block exterior wall has a transmission loss of approximately 55 dB, and with an exterior noise level of about 65 dB, one can see from Fig. 7c that to be within the limits, 32 percent glass is acceptable for this situation. Checking Fig. 8 one can see for a desired AI between classrooms of 0.01 that the STC of the separating partitions must be about 35, which is equivalent to a 6-inch concrete block painted on both sides. Hence the room with typical construction is acceptable. The only remaining check is to specify a ventilating system that is equal to or less than NC-35. This, in turn, places restrictions on the architect-engineer's choice of equipment, since some standardly used equipment produces noise levels that exceed this limit.

CONCLUSIONS

There are a number of conclusions to be drawn from this study. Perhaps the first should be that it is possible, on the basis of extant literature, to determine some of the parameters required for effective speech communication in classrooms. While it is also true that there are some gaps in the literature and research, it is hoped that they may be filled in as a result of being pointed out. A second conclusion would be that it is obvious that little of the acoustical knowledge has actually been applied in classroom design today. While many classroom ceilings today are fully covered with acoustical absorption, this coverage is seldom needed, and is actually a detriment to effective communication. Classroom noise levels, generated by mechanical equipment, are also frequently too high for effective speech intelligibility. While it may be difficult to impossible to determine if the noise level in the classroom is indeed detrimental to learning, obvious questions are raised about the effectiveness of the teacher at the end of the day or about student behavior and retention.

Economic implications are also involved, which may or may not be obvious, since some of the recommendations made in this study may add to the cost of schools, others may subtract some. On balance, it is probably that full application of acoustical knowledge may add somewhat to the cost of schools. However, it also seems that this probability should be viewed in the same context as does good lighting cost more or less than poor lighting; does good thermal control (including air-conditioning) cost more or less than poor thermal control? Cost increments in these areas have been accepted to one degree or another, and in view of the known trends about school design and equipment, pointed out in the introduction, it seems obvious that additional attention must be paid to the acoustical environment of school classrooms.

SUMMARY

Two of the important operative factors in determining, at the design stage, the parameters for effective speech communication in classrooms are: (1) provision for optimum reverberation time, and (2) using the Articulation Index as a predictive tool, determining the maximum masking noise level allowable for effective student-teacher voice communication. Consideration is limited to high school classrooms, since the frequently more formal instructional environment requires speech communication over longer distances than in the elementary classroom.

Using extant acoustic literature, design guidelines in the form of easily interpreted graphs have been constructed for both operative elements. Considerable experience and literature are available for determining optimum reverberation time requirements and the construction of appropriate design guidelines is a straight-formed task. The Articulation Index is a newer concept, and as such it was found that not all the required research and experience is available. However, by making certain rational assumptions, design guidelines have also been constructed for noise levels in classrooms and acoustic separation between classrooms for effective communications, again in the form of easily interpreted graphs.

The basic findings of this study may be summarized rather quickly by stating that, frequently, too much acoustic absorption is applied in classrooms often in the wrong places, and classroom noise levels are often too high for effective speech communication.

However, the job is not yet done. We need to know more about calculational procedures for female voices, since the Articulation Index has been validated only for male speakers, and we need to know much more about the attenuation and distribution of sound from a source in enclosed spaces typical of school classrooms.

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TABLE I

ADDITIONAL ABSORPTION REQUIRED IN OCCUPIED SPACES TO ACHIEVE OPTIMUM REVERBERATION TIME
(Uncarpeted Floor)

Area	Ceiling Height	250 cs	500 cs	1000 cs	2000 cs	Average
650	9	262	219	245	216	235
700	10	322	320	307	275	306
750	11	386	386	373	338	371
700	9	271	264	248	217	250
750	10	332	334	330	298	323
800	11	401	397	381	344	381
800	9	302	293	274	239	277
850	10	370	362	344	305	345
900	11	441	435	417	376	417
1300	10	543	532	506	457	510
1400	11	661	652	627	573	628
1500	12	787	781	757	699	756
1400	10	5[illegible]	546	515	460	521
1500	11	6[illegible]	671	640	581	645
1600	12	816	804	774	711	776
1500	10	585	560	523	463	532
1600	11	711	689	653	588	660
1700	12	846	827	791	723	797
1000	10	829	287	239	181	259
1100	12	489	452	404	339	421
1200	14	666	634	586	514	600
1250	10	395	342	282	213	308
1350	12	579	330	470	411	494
1500	14	811	768	708	623	728
1500	10	460	395	323	243	355
1600	12	675	613	542	457	572
1800	14	952	893	827	730	851
1800	10	544	468	385	294	423
1900	12	779	708	624	525	659
2100	14	1089	1025	942	833	973
2000	10	583	494	398	297	443
2200	12	888	805	711	600	751
2400	14	1225	1149	1056	935	1108

TABLE II

ADDITIONAL ABSORPTION IN OCCUPIED SPACES
(Carpeted Floor)
(Assumed Effective Area of Carpet 50%)

Area	Ceiling Height	Average over 4 frequencies	Sq ft of NRC .80 Absorption Required
650	9	-57	-
700	10	-10	-
750	11	33	41
700	9	-37	-
750	10	-20	-
800	11	20	25
800	9	-83	-
850	10	-37	-
900	11	12	15
1300	10	-19	-
1400	11	-2	-
1500	12	81	101
1400	10	-109	-
1500	11	-126	-
1600	12	56	70
1500	10	-143	-
1600	11	-60	-
1700	12	31	39
1000	10	-191	-
1100	12	-74	-
1200	14	60	75
1250	10	-255	-
1350	12	-137	-
1500	14	65	52
1500	10	-400	-
1600	12	-185	-
1800	14	50	40
1800	10	-485	-
1900	12	-242	-
2100	14	38	27
2000	10	-571	-
2200	12	-299	-
2400	14	14	11

Note: These values are for the average of the six material options shown in Appendix I.

TABLE III - TABULATION OF AI VALUE VS. NC LEVELS
NORMAL VOICE

Room Constant sq ft	NC-25	NC Levels, NC-35 Articulation Index	NC-45
520	1.0	0.851	0.527
653	1.0	0.817	0.493
763	1.0	0.817	0.493
588	1.0	0.851	0.527
690	1.0	0.817	0.493
850	1.0	0.783	0.459
655	1.0	0.817	0.493
808	1.0	0.783	0.459
932	1.0	0.783	0.459
1075	1.0	0.750	0.426
1254	1.0	0.716	0.392
1451	1.0	0.716	0.392
1152	1.0	0.750	0.426
1328	1.0	0.716	0.392
1530	1.0	0.682	0.358
1210	1.0	0.716	0.392
1400	1.0	0.716	0.392
1607	1.0	0.682	0.358
816	1.0	0.783	0.459
1133	1.0	0.750	0.426
1447	1.0	0.716	0.392
1040	1.0	0.750	0.426
1333	1.0	0.716	0.392
1723	1.0	0.682	0.358
1209	1.0	0.716	0.392
1566	1.0	0.682	0.358
1992	0.996	0.648	0.324
1408	1.0	0.716	0.392
1760	1.0	0.682	0.358
2377	0.962	0.614	0.290
1539	1.0	0.682	0.358
2100	0.996	0.648	0.324
2650	0.928	0.581	0.257
500-600	1.0	0.851	
600-800	1.0	0.817	
800-1000	1.0	0.783	
1000-1200	1.0	0.750	
1200-1500	1.0	0.716	
1500-1900	1.0		
1900-2300	0.996		
2300-2600	0.962		
2600-2800	0.928		

TABLE IV - TABULATION OF AI VALUE VS. NC LEVELS
RAISED VOICE

Room Constant sq ft	NC-25	NC Levels, NC-35 Articulation Index	NC-45
520	1.0	0.0	0.735
653	1.0	0.0	0.701
763	1.0	1.0	0.701
588	1.0	1.0	0.735
690	1.0	1.0	0.701
850	1.0	0.991	0.667
655	1.0	1.0	0.701
808	1.0	0.991	0.667
932	1.0	0.991	0.667
1075	1.0	0.957	0.633
1254	1.0	0.924	0.600
1451	1.0	0.924	0.600
1152	1.0	0.957	0.633
1328	1.0	0.924	0.600
1530	1.0	0.890	0.566
1210	1.0	0.924	0.600
1400	1.0	0.924	0.600
1607	1.0	0.89	0.566
816	1.0	0.991	0.667
1133	1.0	0.957	0.633
1447	1.0	0.924	0.600
1140	1.0	0.957	0.633
1333	1.0	0.924	0.600
1723	1.0	0.890	0.566
1209	1.0	0.924	0.600
1566	1.0	0.890	0.566
1992	1.0	0.856	0.532
1408	1.0	0.924	0.600
1760	1.0	0.890	0.566
2377	1.0	0.822	0.569
1539	1.0	0.890	0.566
2100	1.0	0.856	0.532
2650	1.0	0.788	0.464
500-650	1.0	1.0	0.735
650-800	1.0	1.0	0.701
800-1050	1.0	0.991	
1050-1200	1.0	0.957	
1200-1450	1.0	0.924	
1450-1800	1.0	0.890	
1800-2100	1.0	0.856	
2100-2400	1.0	0.822	
2400-2700	1.0	0.788	

APPENDIX I

Assumed Sound Absorption Coefficients for
Various Classroom Materials

	Frequencies (Hertz)			
Material	250	500	1000	2000
Chalk Board	0.01	0.02	0.04	0.04
Windows	0.25	0.18	0.12	0.07
"Hard" Ceiling	0.01	0.02	0.02	0.03
"Soft" Ceiling	0.06	0.04	0.03	0.05
"Hard" Walls	0.01	0.02	0.03	0.04
"Soft" Walls	0.10	0.05	0.04	0.07
Hard Floor	0.01	0.02	0.03	0.04
Carpeting	0.46	0.42	0.50	0.53

APPENDIX II

Form of Calculation of Articulation Index

Col. 1 Octave Bands	Col. 2 Voice Power Level	Col. 3 Atten-uation	Col. 4 Masking	Col. 5 Weight	Col. 6 Col. 5 x Col. 2-Col. 3-Col. 4
150-300 Hz	85	-24	47	0.0017	
300-600	88	(Typical value)	41	0.0040	
600-1200	88		38	0.0067	
1200-2400	85		35	0.0107	
2400-4800	77		34	0.0087	
4800-9600	64		32	0.0020	
					AI =

Col. 1 - Octave Band Widths, Commercial Filters

Col. 2 - Sound Power Level, dB re 10^{-12} watt, raised voice, plus 12 dB to represent speech peaks, average for men's and women's voices.

Col. 3 - From Fig. 4, for distances of 20 feet - 40 feet and for the previously calculated room constants.

Col. 4 - Masking Levels are Octave Band Sound Pressure Levels for the various NC Contours Considered - NC-25, 35, 45.

Col. 5 - Weighting fraction, from Kryter.

Col. 6 - Summation of Col. 6 equals the AI.

COMPARISON OF AI CALCULATIONS

NORMAL VOICE LEVEL

Assume NC of 45 - A Rel. SPL Loss of 20

Kryter (Converting to Sound Power Levels from Sound Pressure Levels)

76 - 20	= 56 + 12	= 68 - 54	= 14 x 0.0017	=	0.0230
80 - 20	= 60 + 12	= 72 - 49	= 23 x 0.0040	=	0.0922
74 - 20	= 54 + 12	= 66 - 46	= 20 x 0.0067	=	0.1340
68 - 20	= 48 + 12	= 60 - 44	= 16 x 0.0107	=	0.1715
65 - 20	= 45 + 12	= 57 - 43	= 14 x 0.0087	=	0.1220
57 - 20	= 37 + 12	= 49 - 42	= 7 x 0.0020	=	0.0140
			AI	=	0.5567

After Beranek

73 - 20	= 53 + 12	= 56 - 54	= 11 x 0.0017	=	0.0188
78 - 20	= 58 + 12	= 70 - 49	= 21 x 0.0040	=	0.0840
79 - 20	= 59 + 12	= 71 - 46	= 25 x 0.0067	=	0.1680
73 - 20	= 53 + 12	= 65 - 44	= 21 x 0.0107	=	0.2250
65 - 20	= 45 + 12	= 57 - 43	= 14 x 0.0087	=	0.1220
52 - 20	= 32 + 12	= 44 - 42	= 2 x 0.0020	=	0.0040
			AI	=	0.6218

After Fletcher - a minimum for both female and male voices

73 - 20	= 53 + 12	= 65 - 54	= 11 x 0.0017	=	0.0188
76 - 20	= 56 + 12	= 68 - 49	= 19 x 0.0040	=	0.0760
76 - 20	= 56 + 12	= 68 - 46	= 22 x 0.0067	=	0.1480
73 - 20	= 53 + 12	= 65 - 44	= 21 x 0.0107	=	0.2250
63 - 20	= 43 + 12	= 55 - 43	= 12 x 0.0087	=	0.1040
52 - 20	= 32 + 12	= 44 - 42	= 2 x 0.0020	=	0.0080
			AI	=	0.5758

SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC .90
NON - CARPETED FLOORS

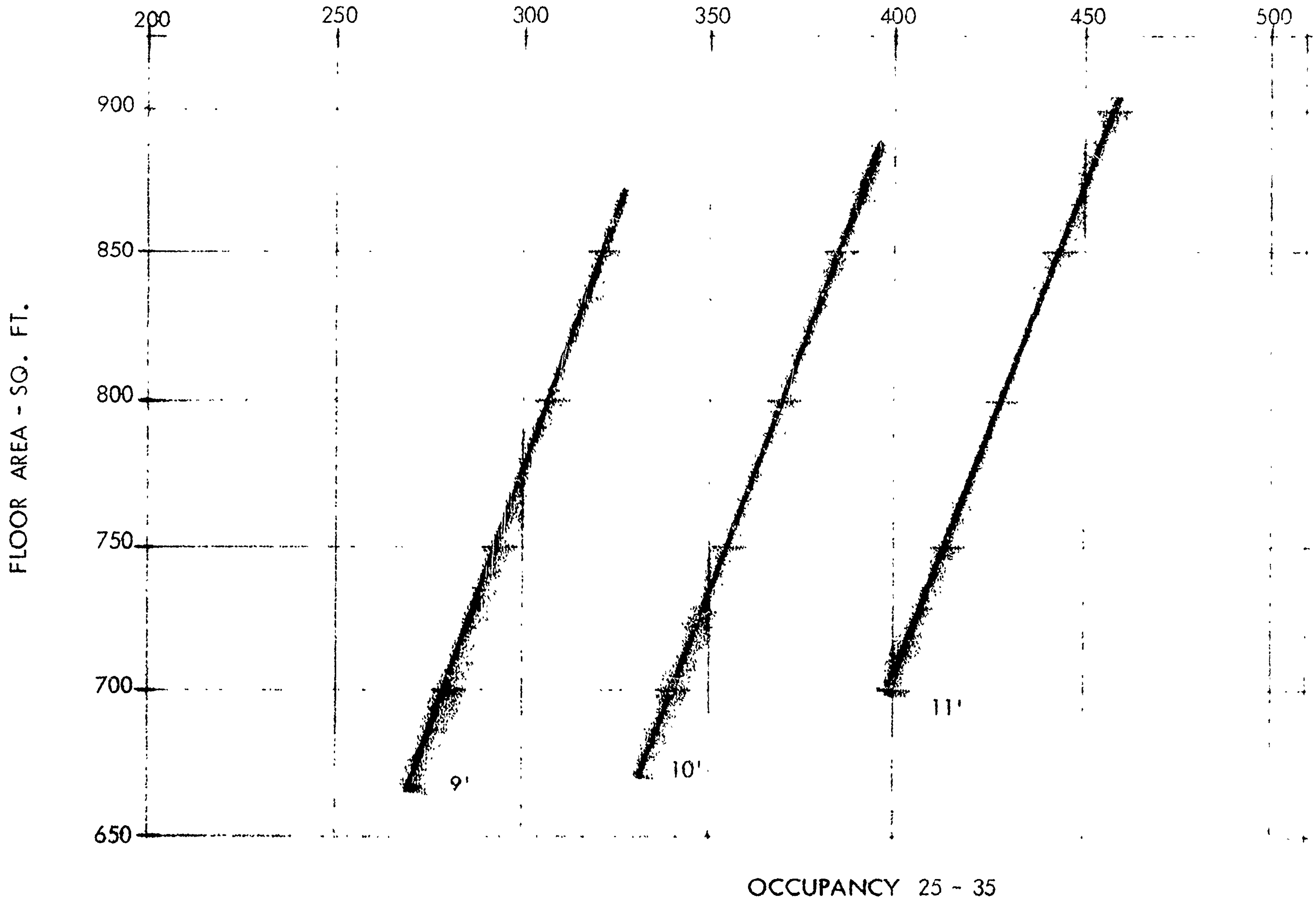


FIG. 1a

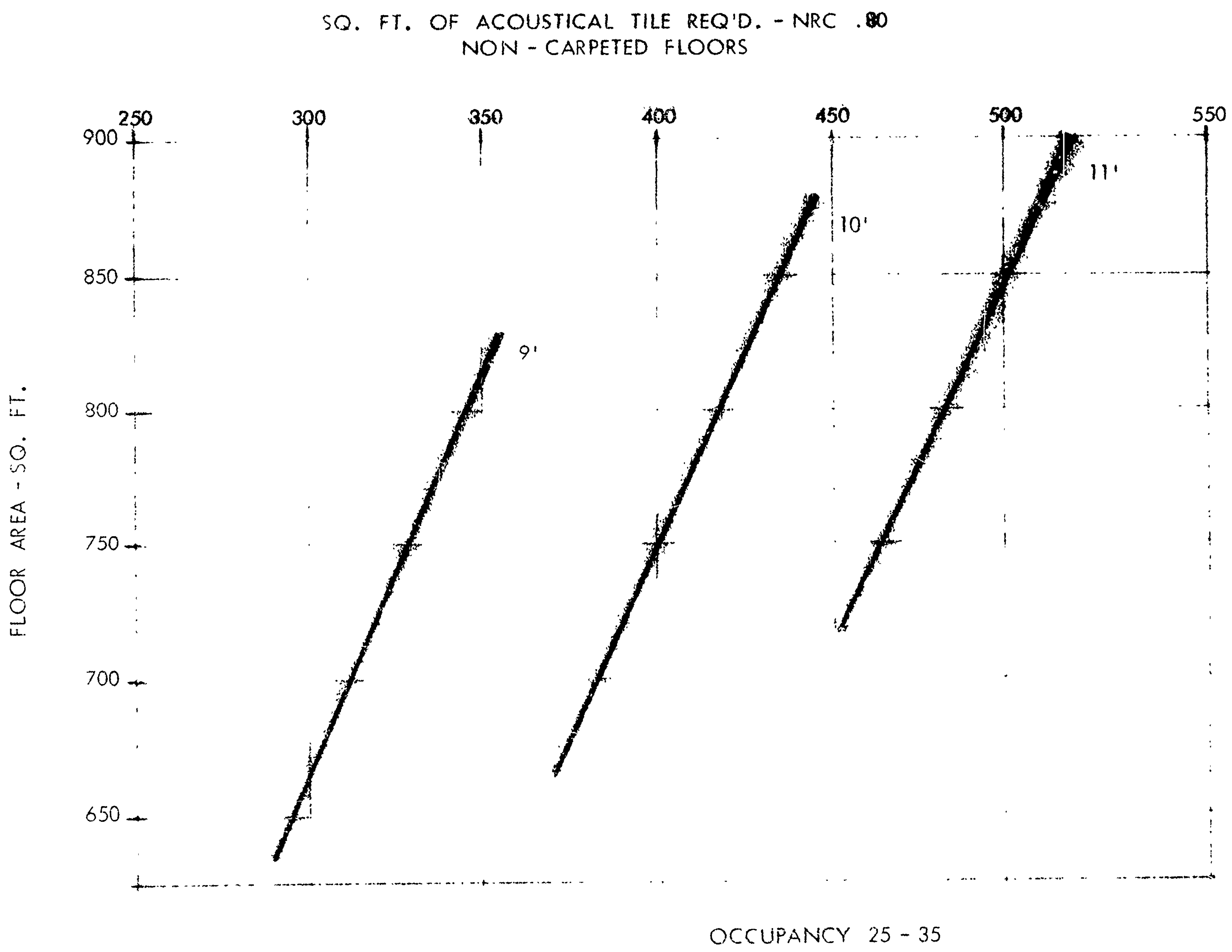

SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC .80
NON - CARPETED FLOORS
250
300
350
400
450
500
550
900
850
800
750
700
650
9'
10'
11'
FLOOR AREA - SQ. FT.
OCCUPANCY 25 - 35

FIG. 1b

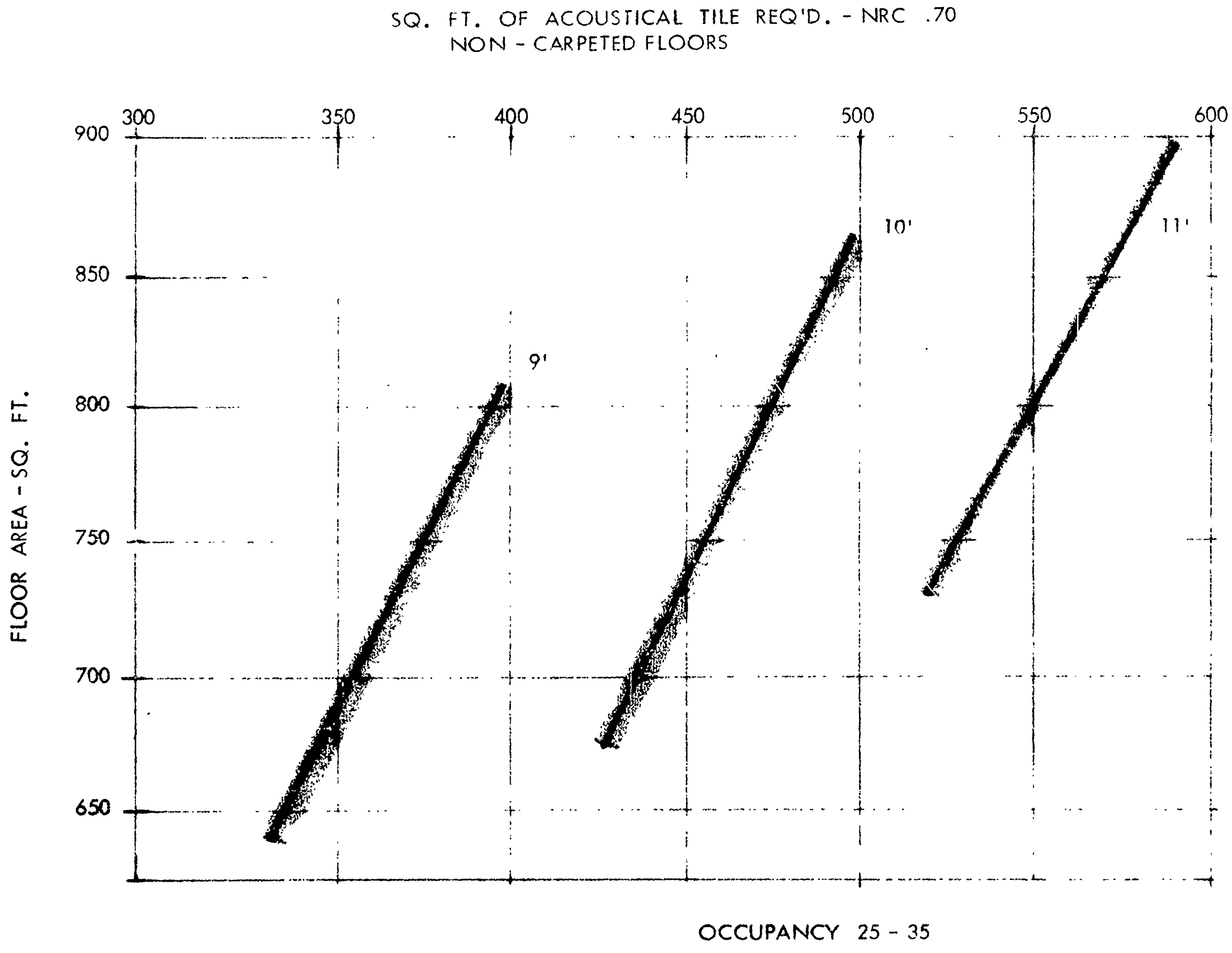

SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC .70
NON - CARPETED FLOORS
300
350
400
450
500
550
600
900
850
800
750
700
650
9'
10'
11'
FLOOR AREA - SQ. FT.
OCCUPANCY 25 - 35

FIG. 1c

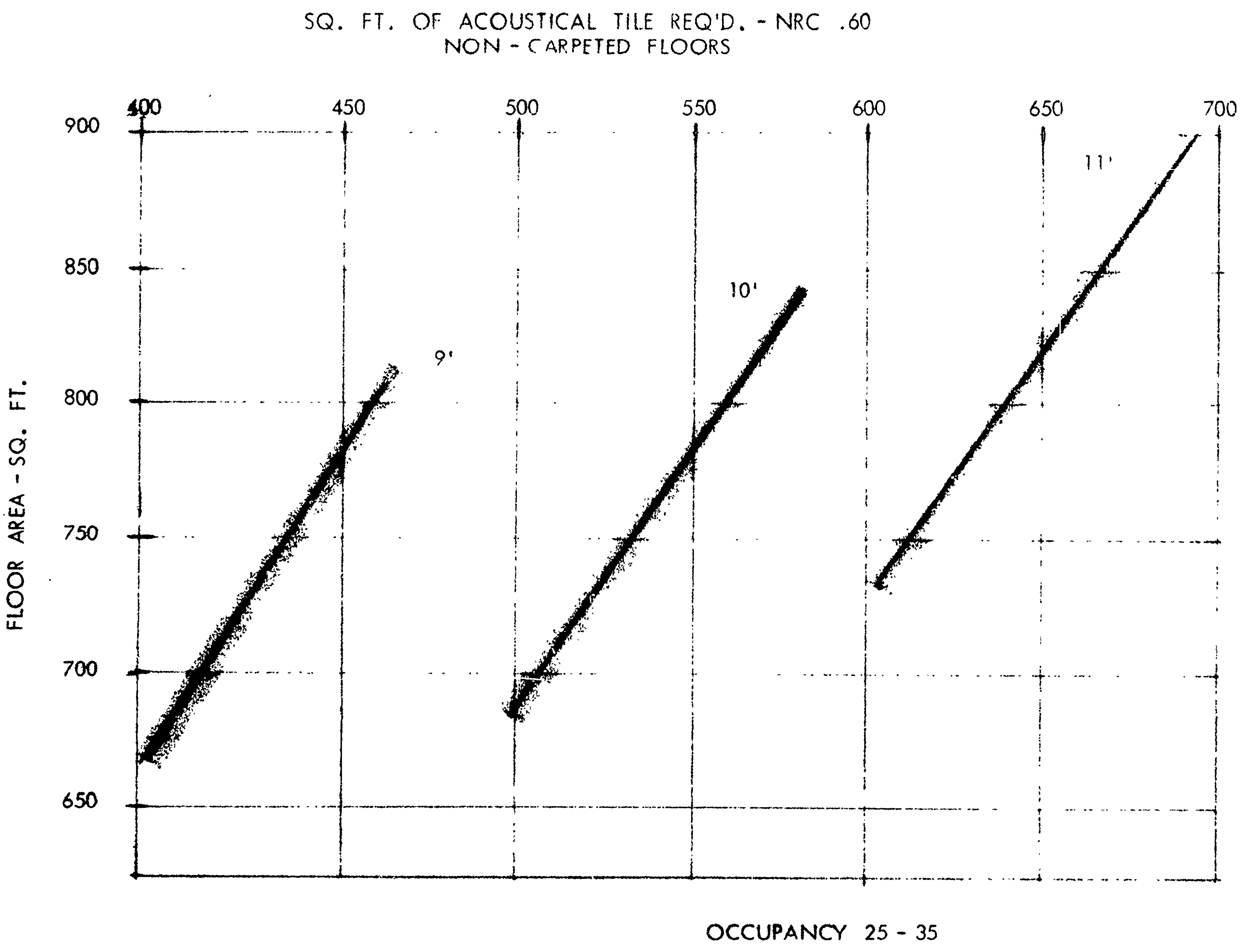

SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC .60
NON - CARPETED FLOORS
400
450
500
550
600
650
700
900
850
800
750
700
650
9'
10'
11'
FLOOR AREA - SQ. FT.
OCCUPANCY 25 - 35

FIG. 1d

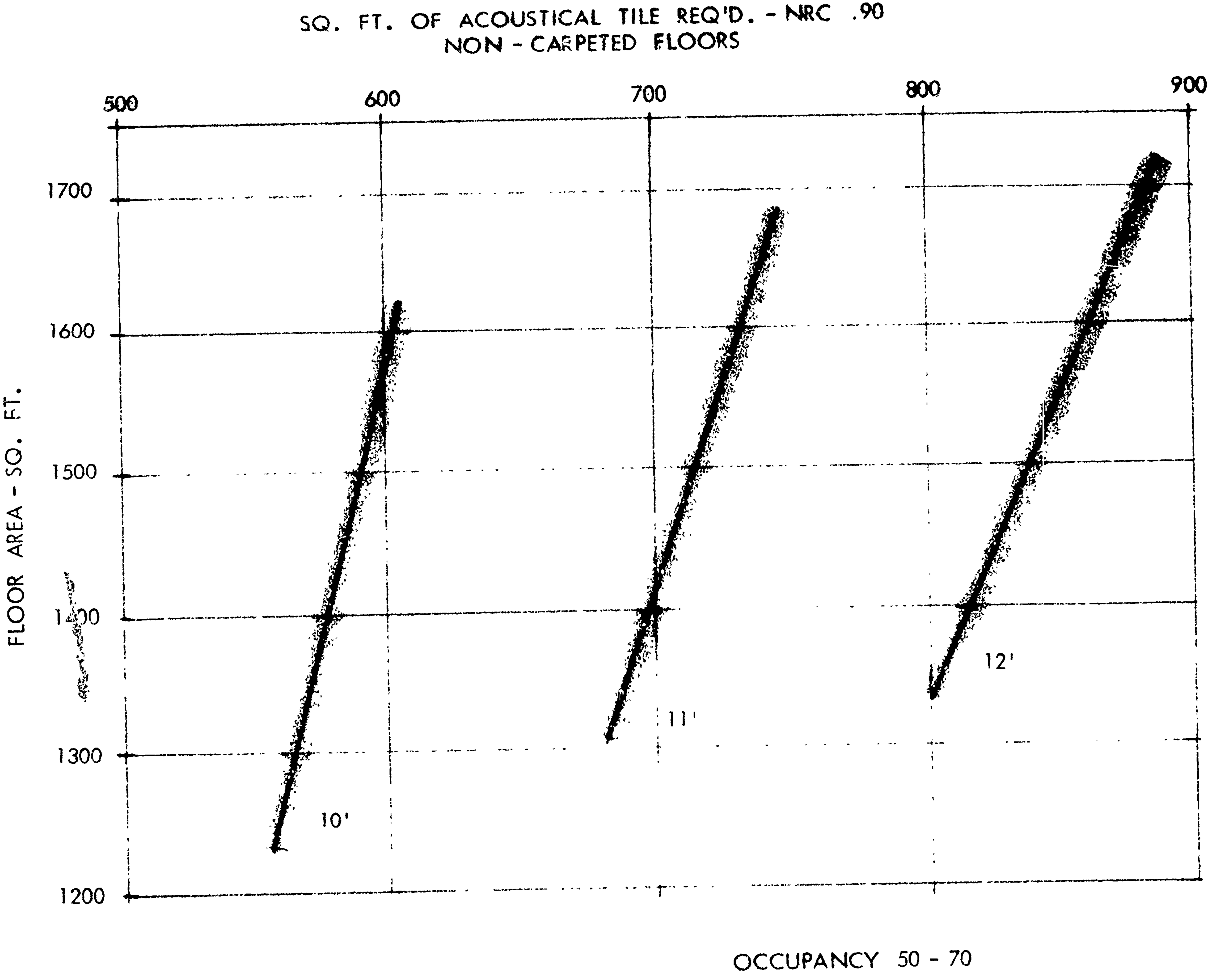
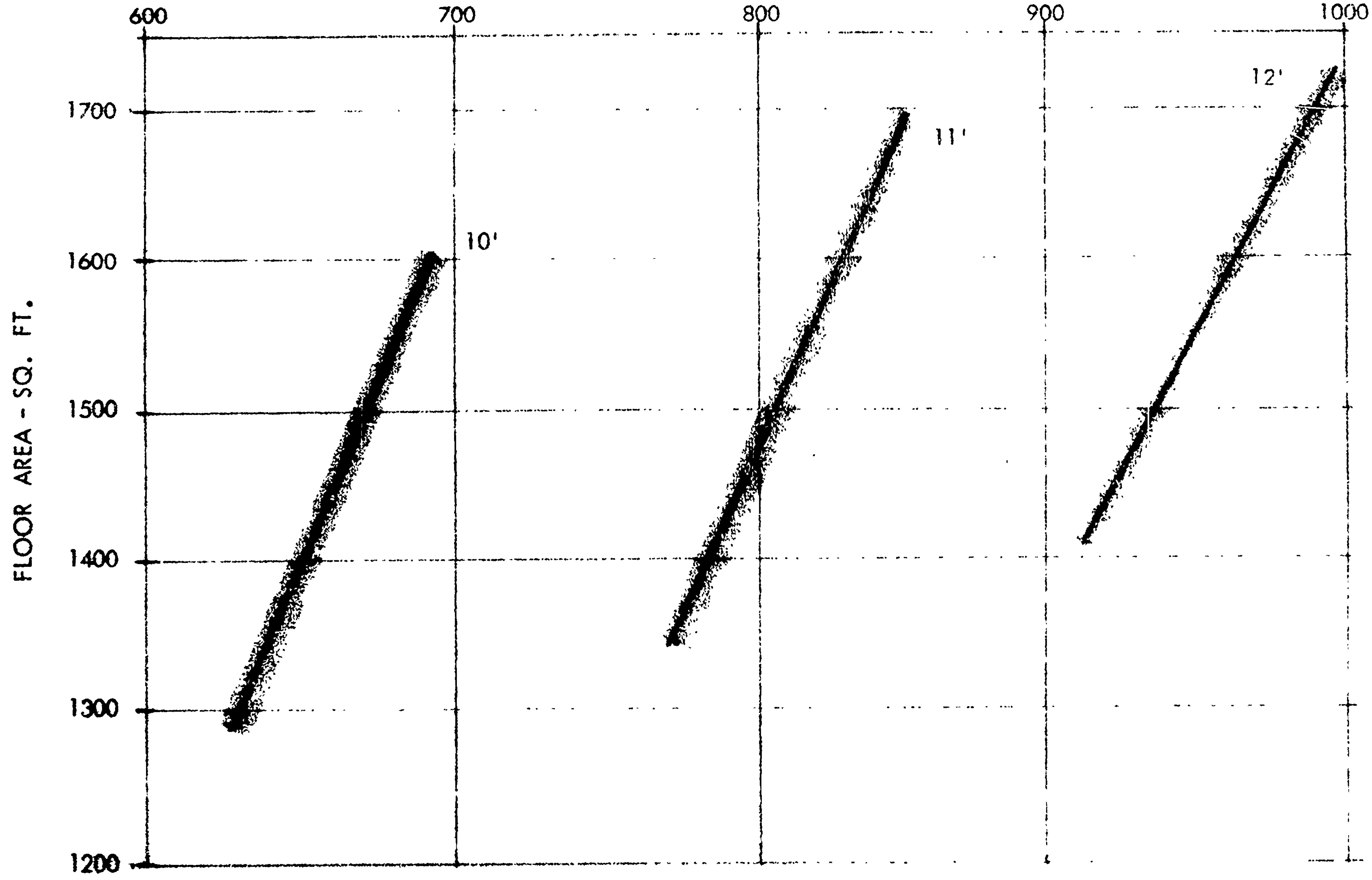

SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC .90
NON - CARPETED FLOORS
500
600
700
800
900
1700
1600
1500
1400
1300
1200
FLOOR AREA - SQ. FT.
10'
11'
12'
OCCUPANCY 50 - 70

FIG. 1e

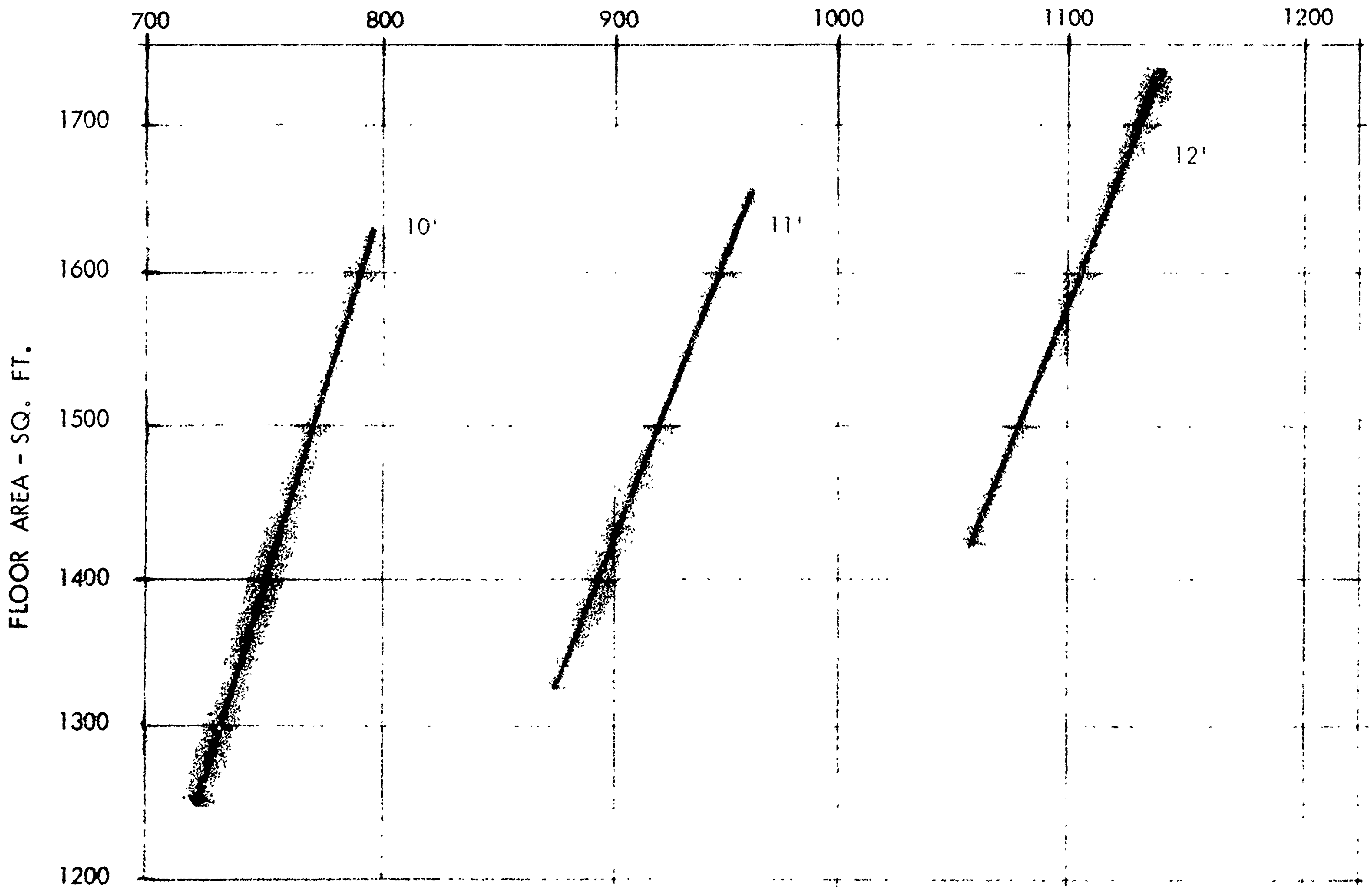
SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC .80
NON - CARPETED FLOORS



OCCUPANCY 50 - 70

FIG. 1f

SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC .70
NON - CARPETED FLOORS



OCCUPANCY 50 - 70

FIG. 1g

SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC .60
NON - CARPETED FLOORS

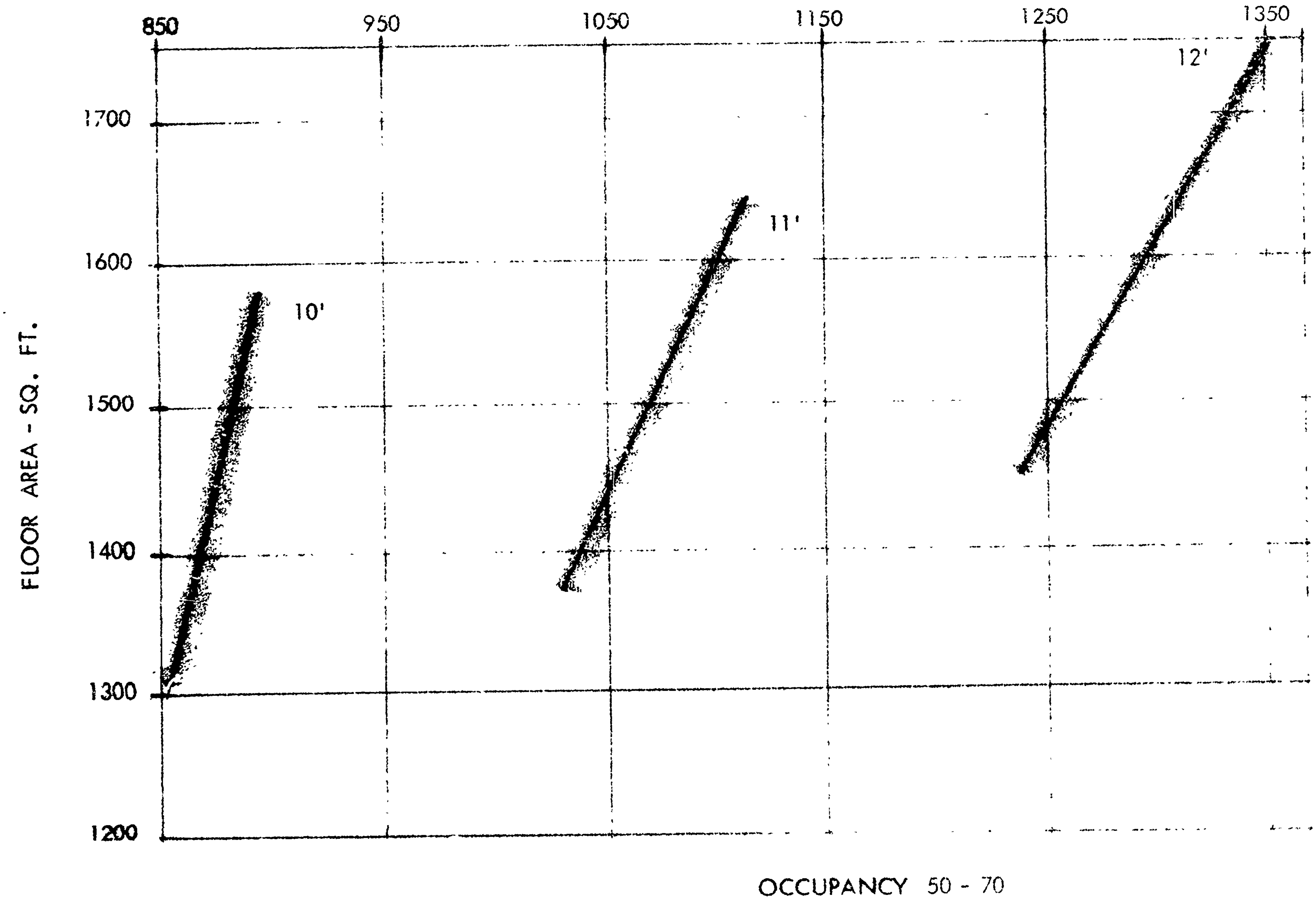


FIG. 1h

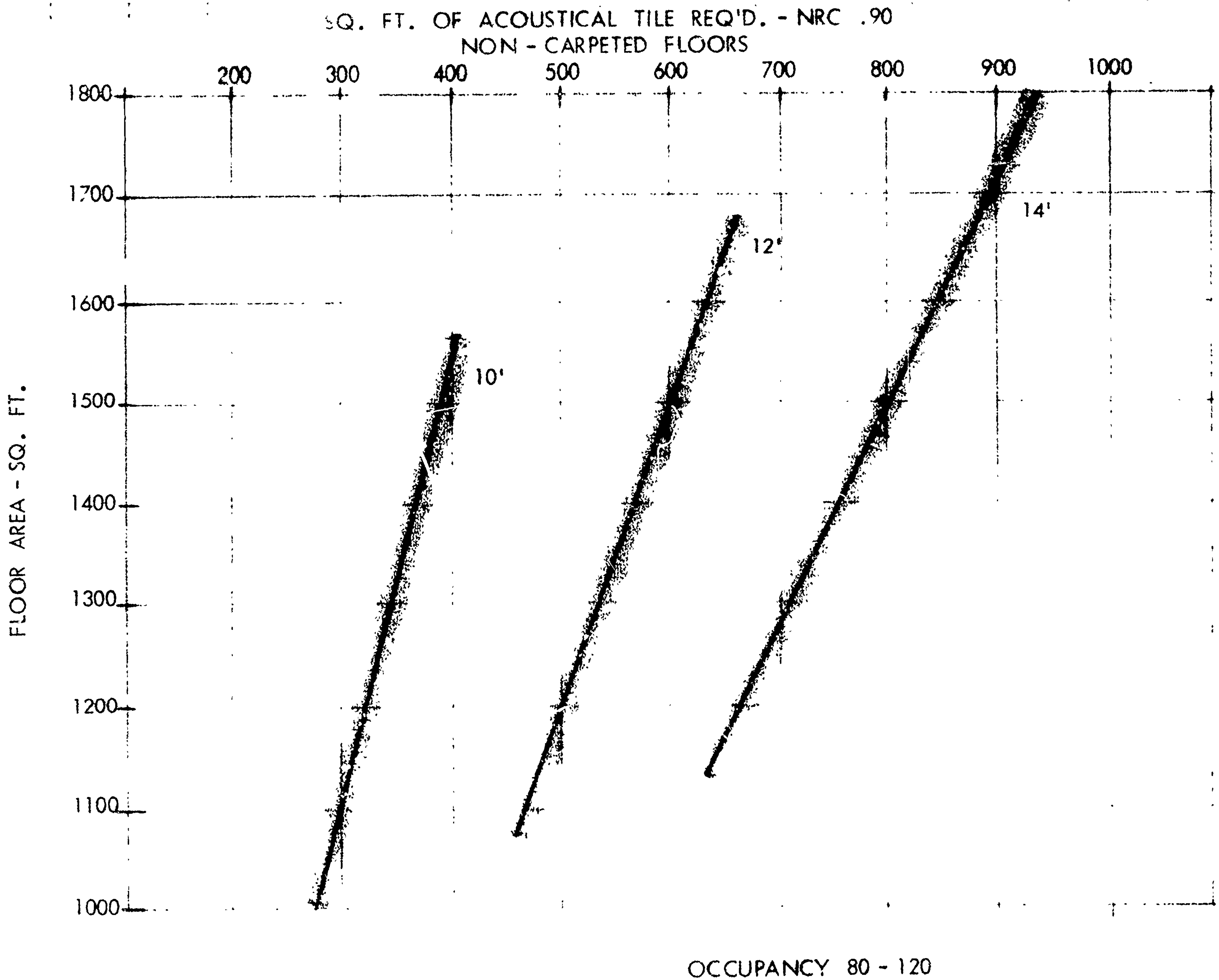
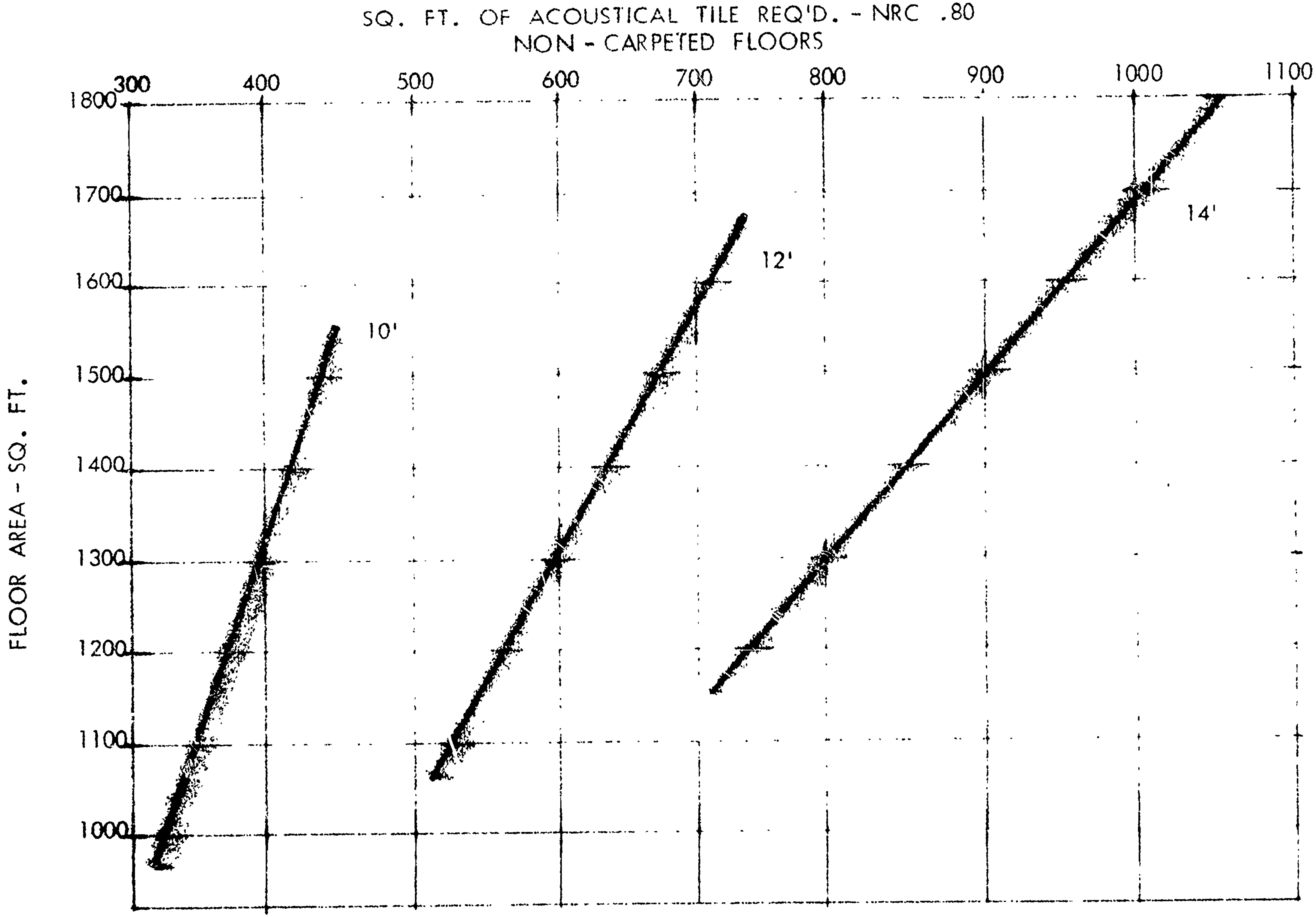

SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC .90
NON - CARPETED FLOORS
200
300
400
500
600
700
800
900
1000
1800
1700
1600
1500
1400
1300
1200
1100
1000
FLOOR AREA - SQ. FT.
10'
12'
14'
OCCUPANCY 80 - 120

FIG. 1i



OCCUPANCY 80 - 120

FIG. 1j

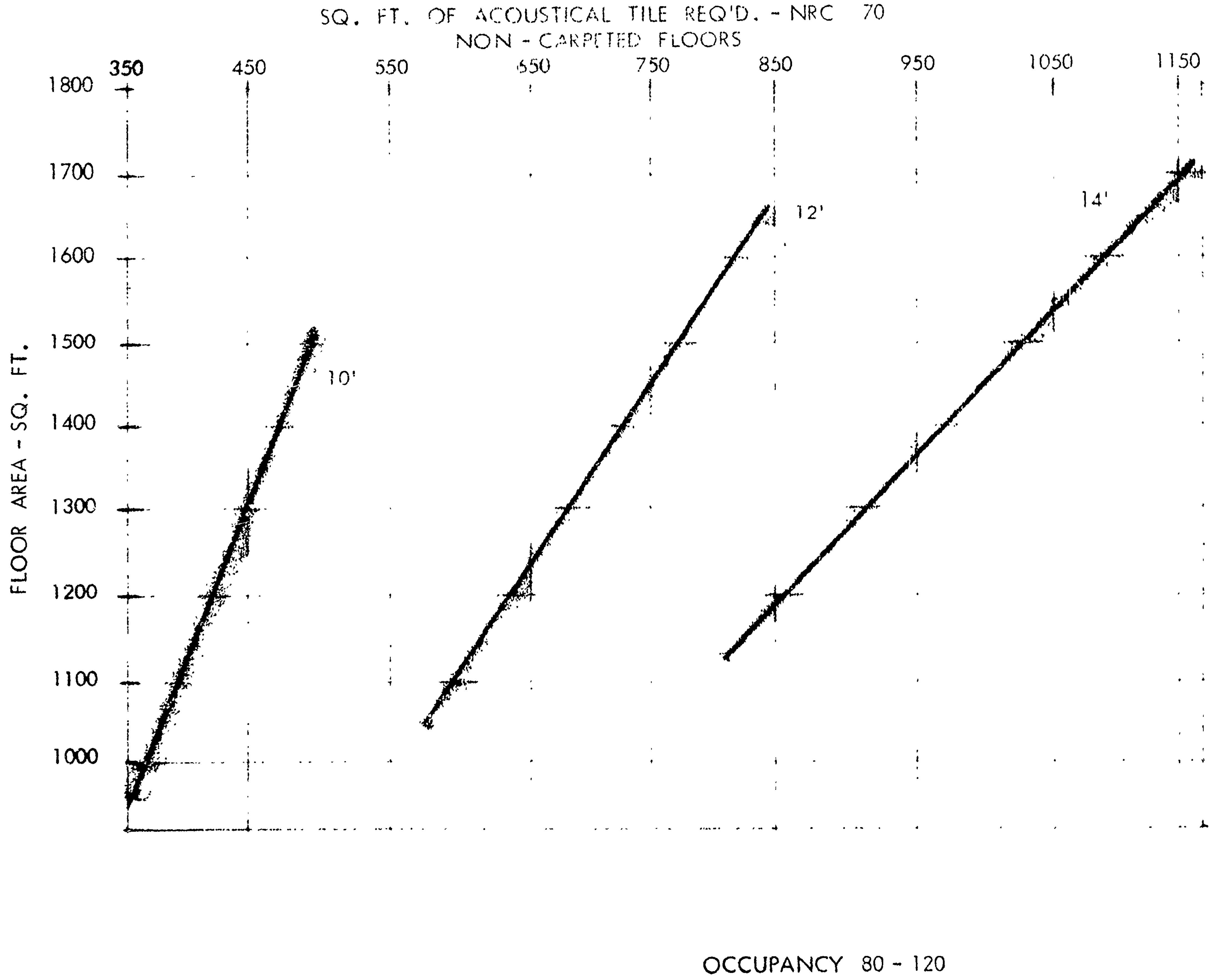
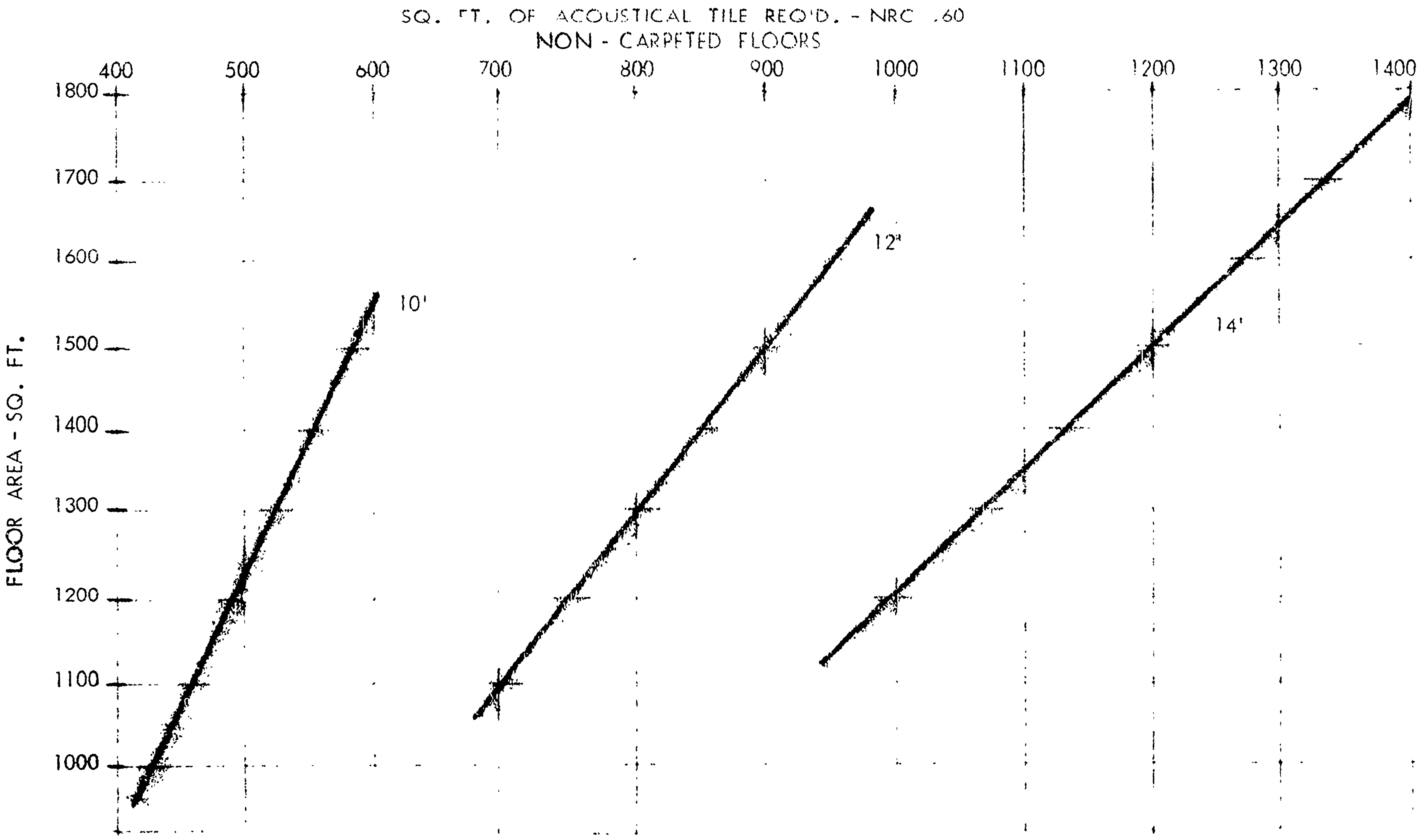

SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC 70
NON - CARPETED FLOORS
350
450
550
650
750
850
950
1050
1150
1800
1700
1600
1500
1400
1300
1200
1100
1000
FLOOR AREA - SQ. FT.
10'
12'
14'
OCCUPANCY 80 - 120

FIG. 1k



OCCUPANCY 80 - 120

FIG. 11

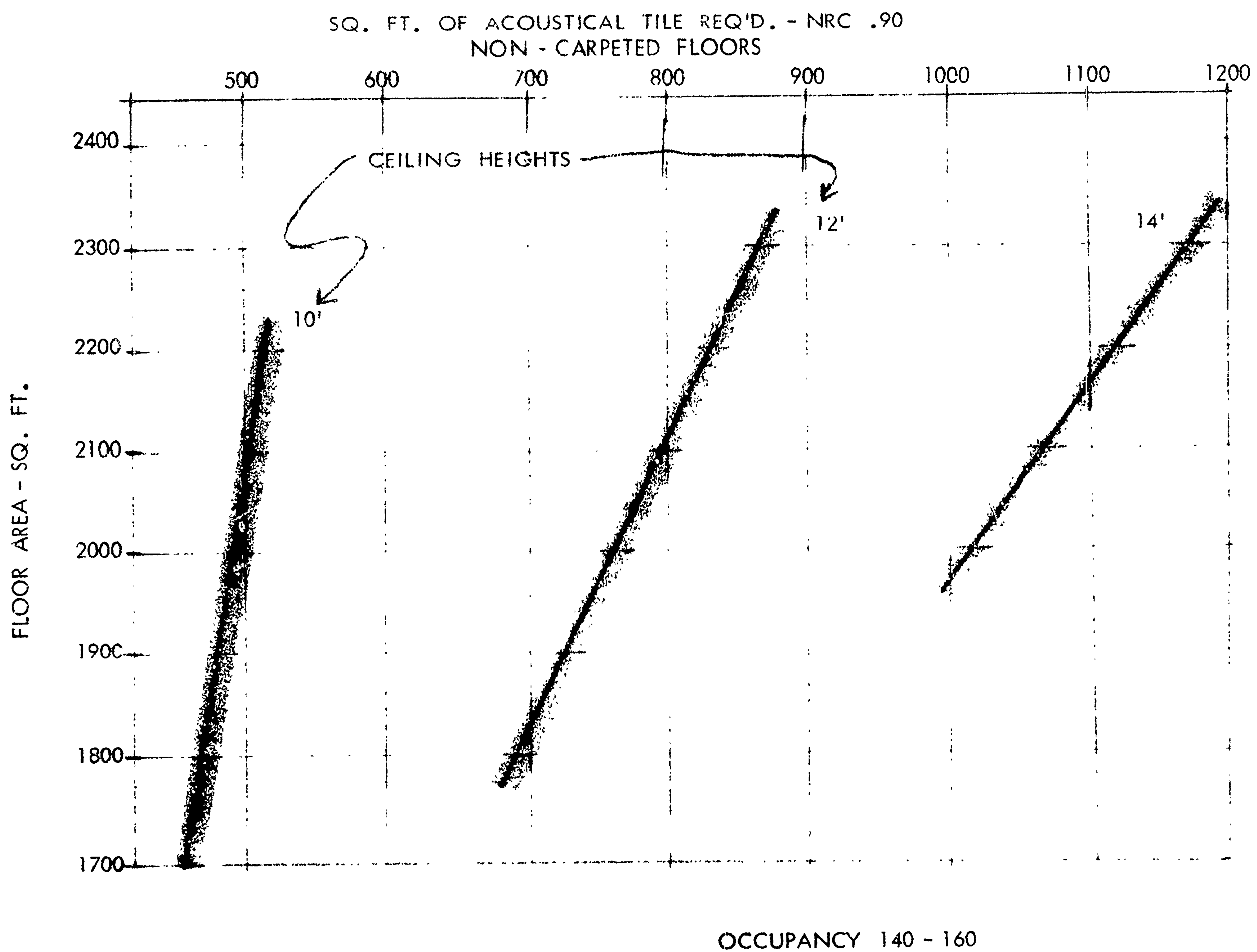
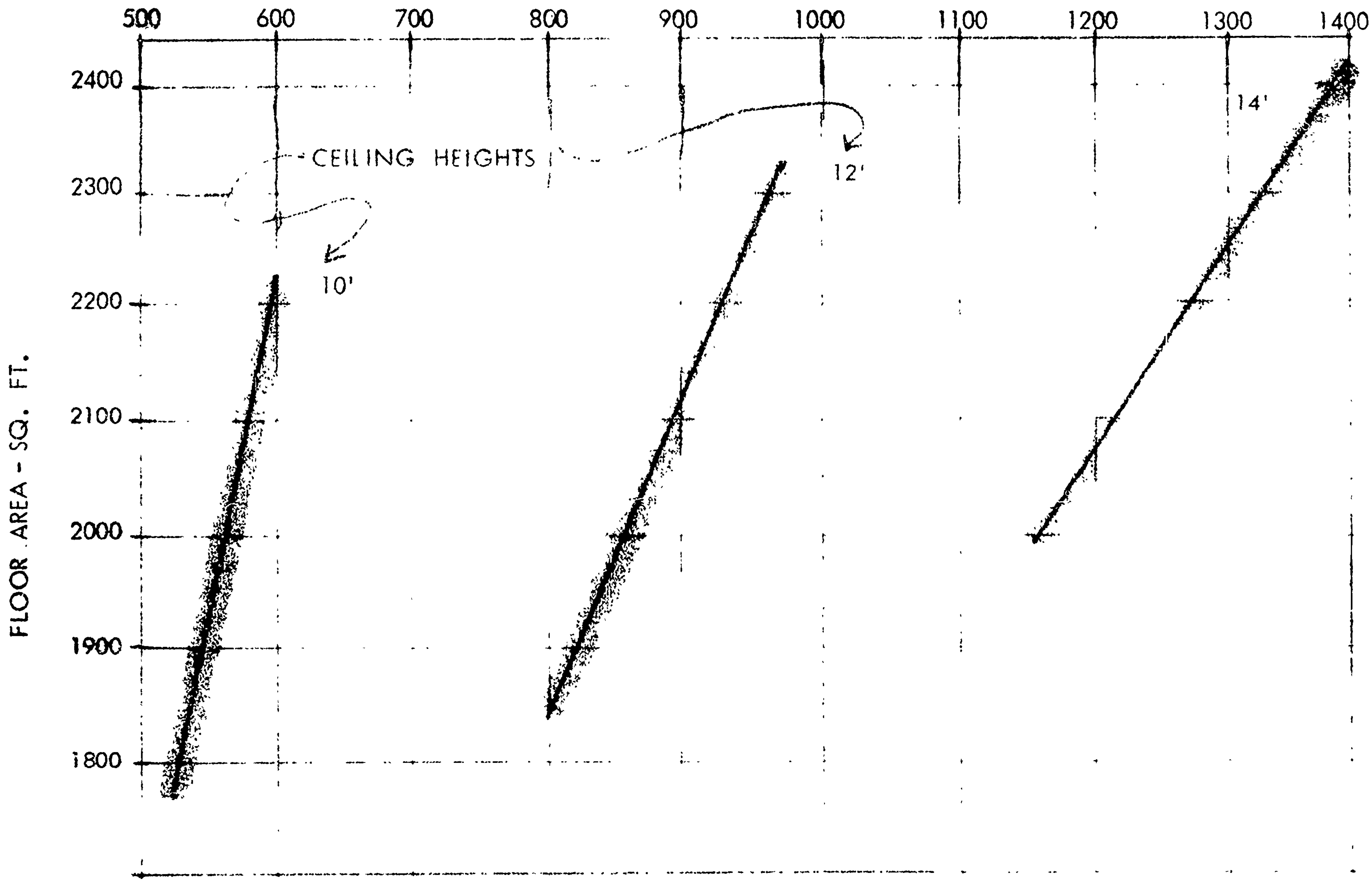

SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC .90
NON - CARPETED FLOORS
500
600
700
800
900
1000
1100
1200
CEILING HEIGHTS
10'
12'
14'
FLOOR AREA - SQ. FT.
2400
2300
2200
2100
2000
190C
1800
1700
OCCUPANCY 140 - 160

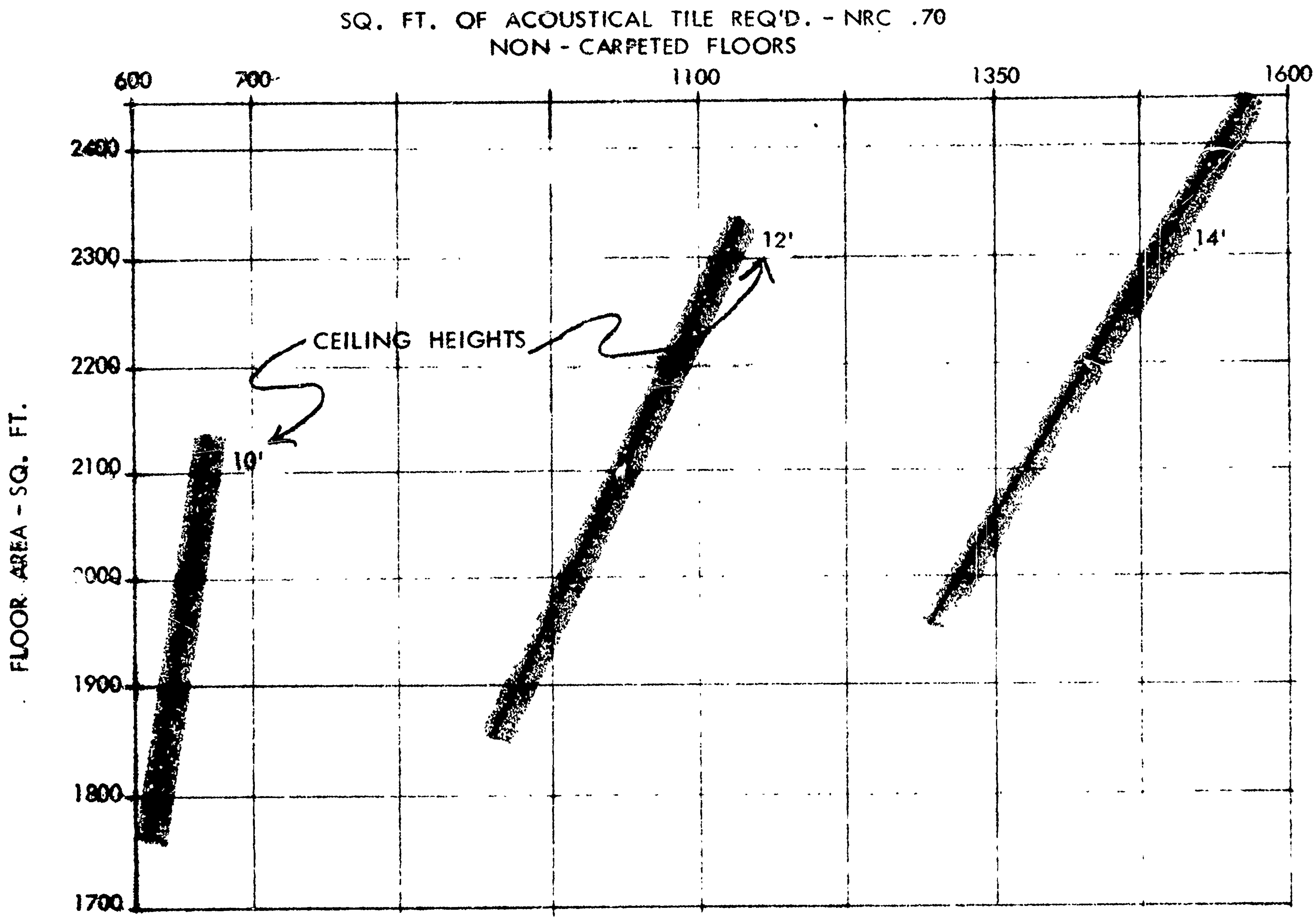
FIG. 1m

SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC .80
NON - CARPETED FLOORS



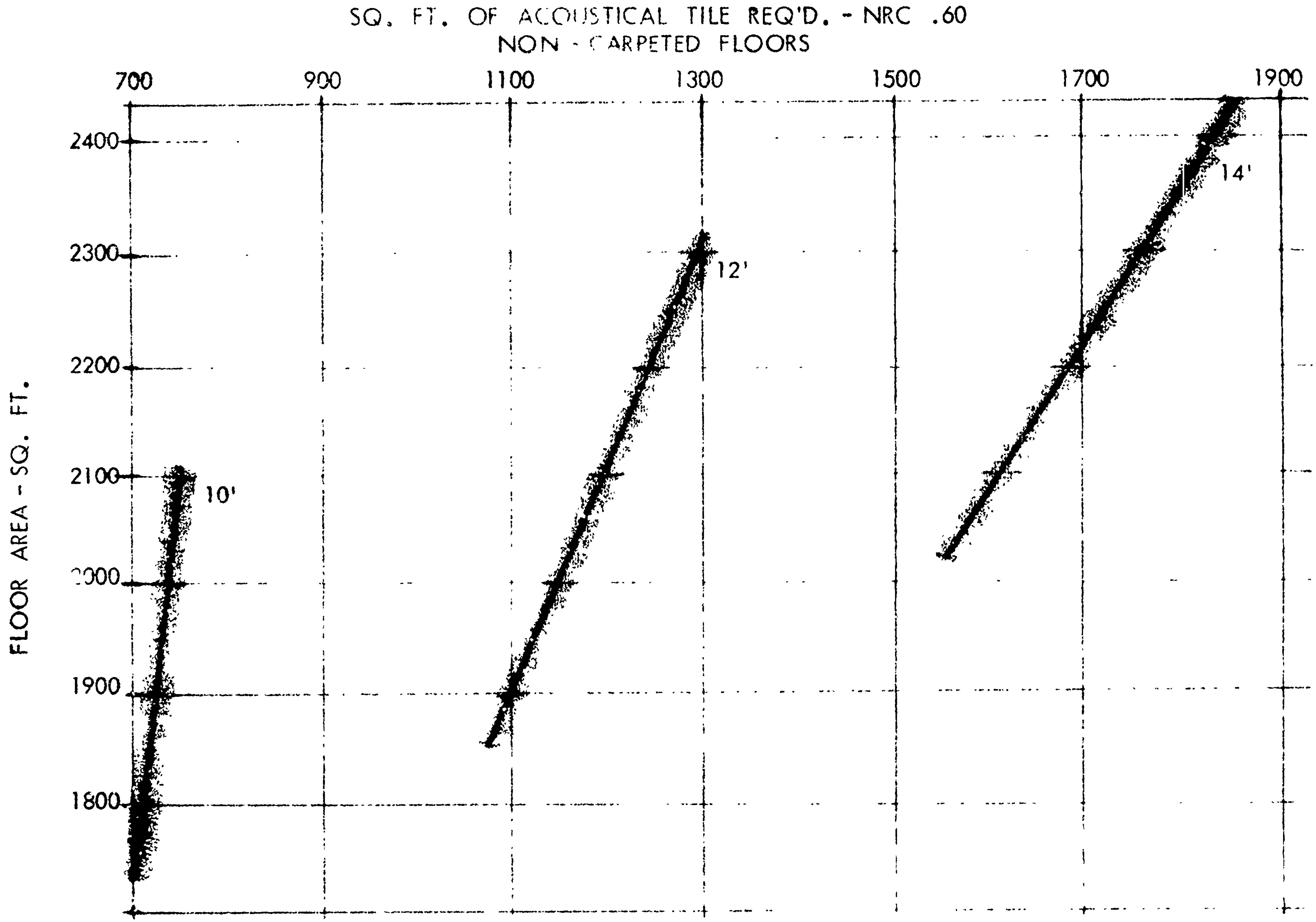
OCCUPANCY 140 - 160

FIG. 1n



OCCUPANCY 140 - 160

FIG. 1o



OCCUPANCY 140 - 160

FIG. 1p

SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC .80
CARPETED FLOORS

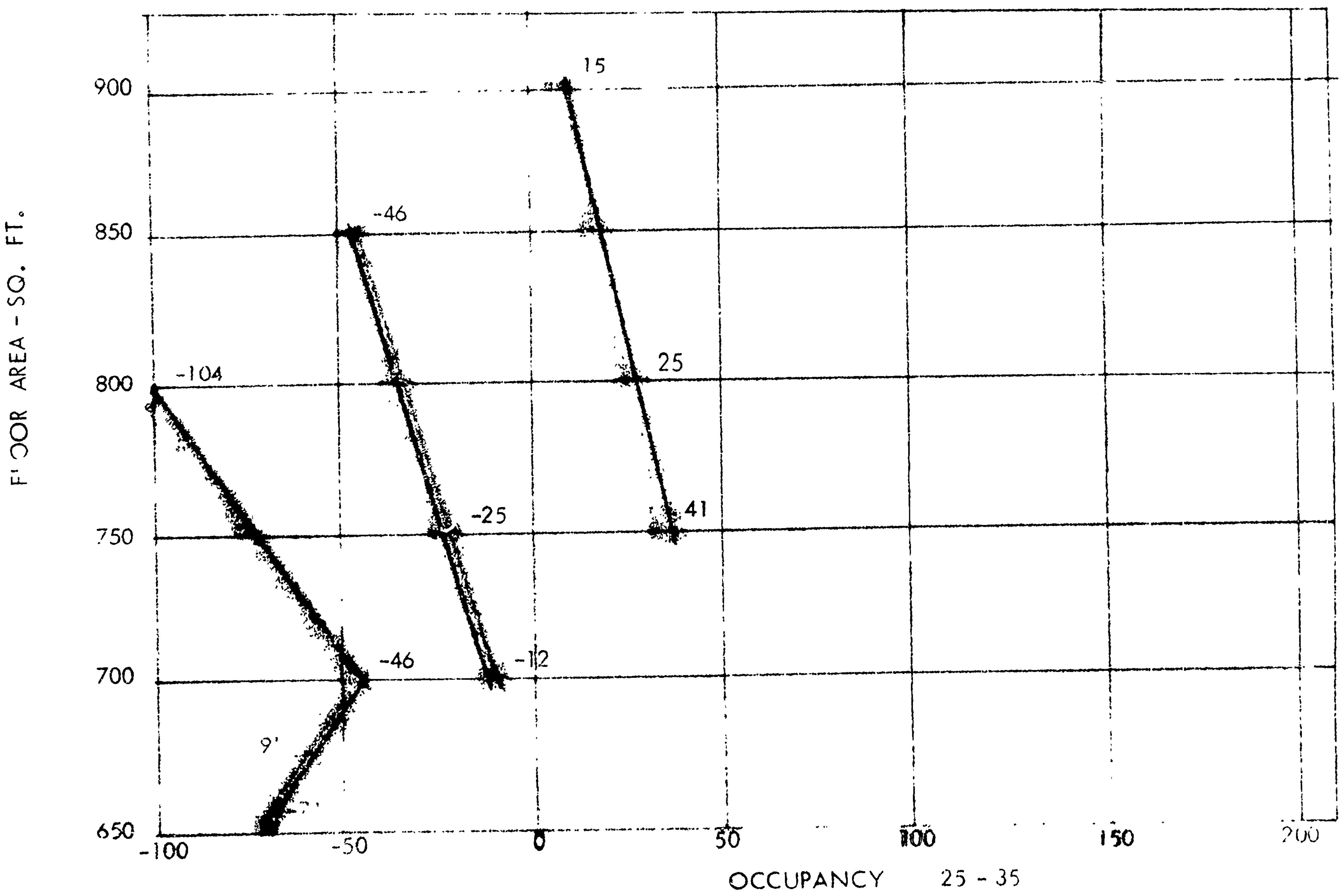


FIG. 2a

SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC .80
CARPETED FLOORS

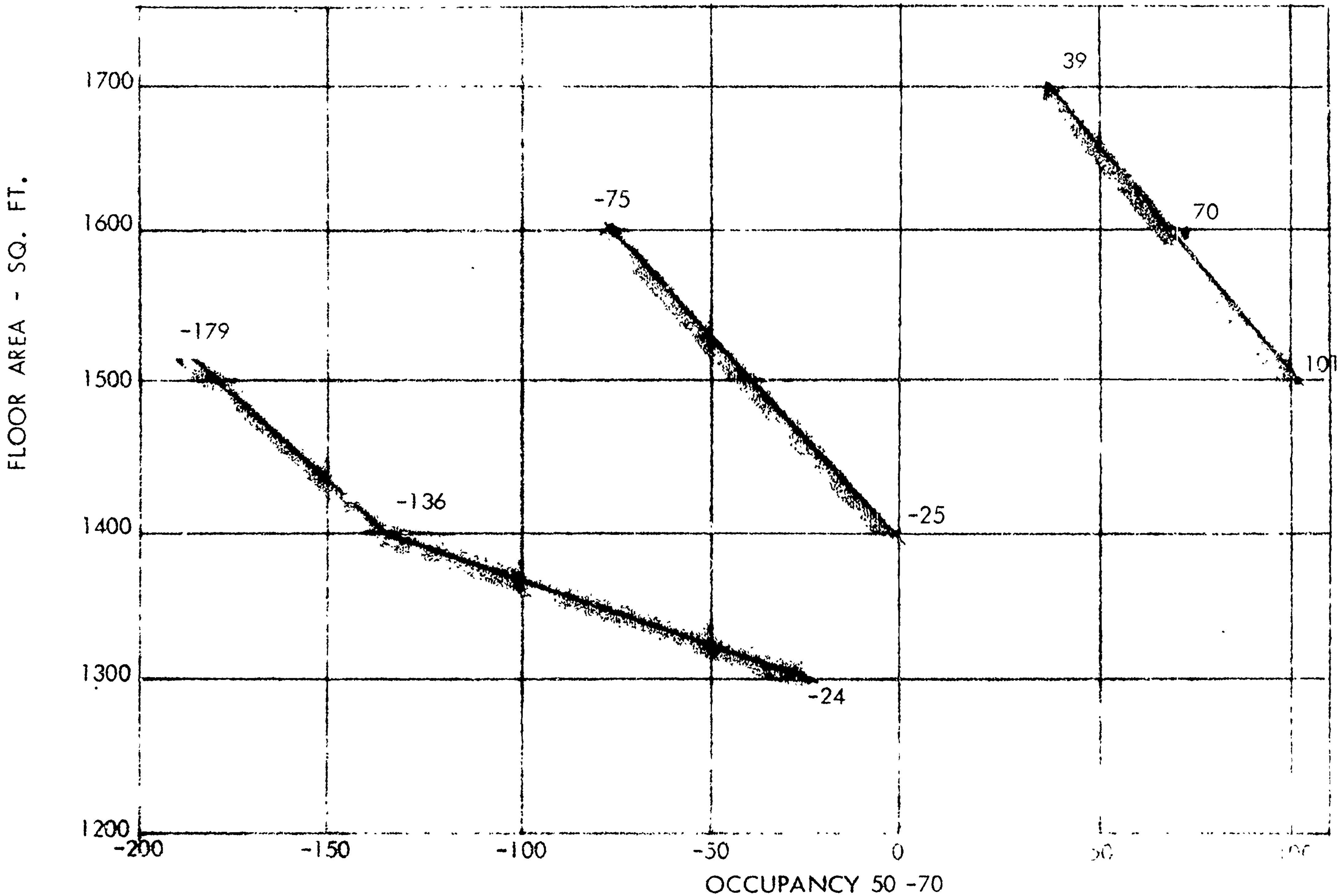


FIG. 2b

SQ. FT. OF ACOUSTICAL TILE REQ'D - NRC .80
CARPETED FLOORS

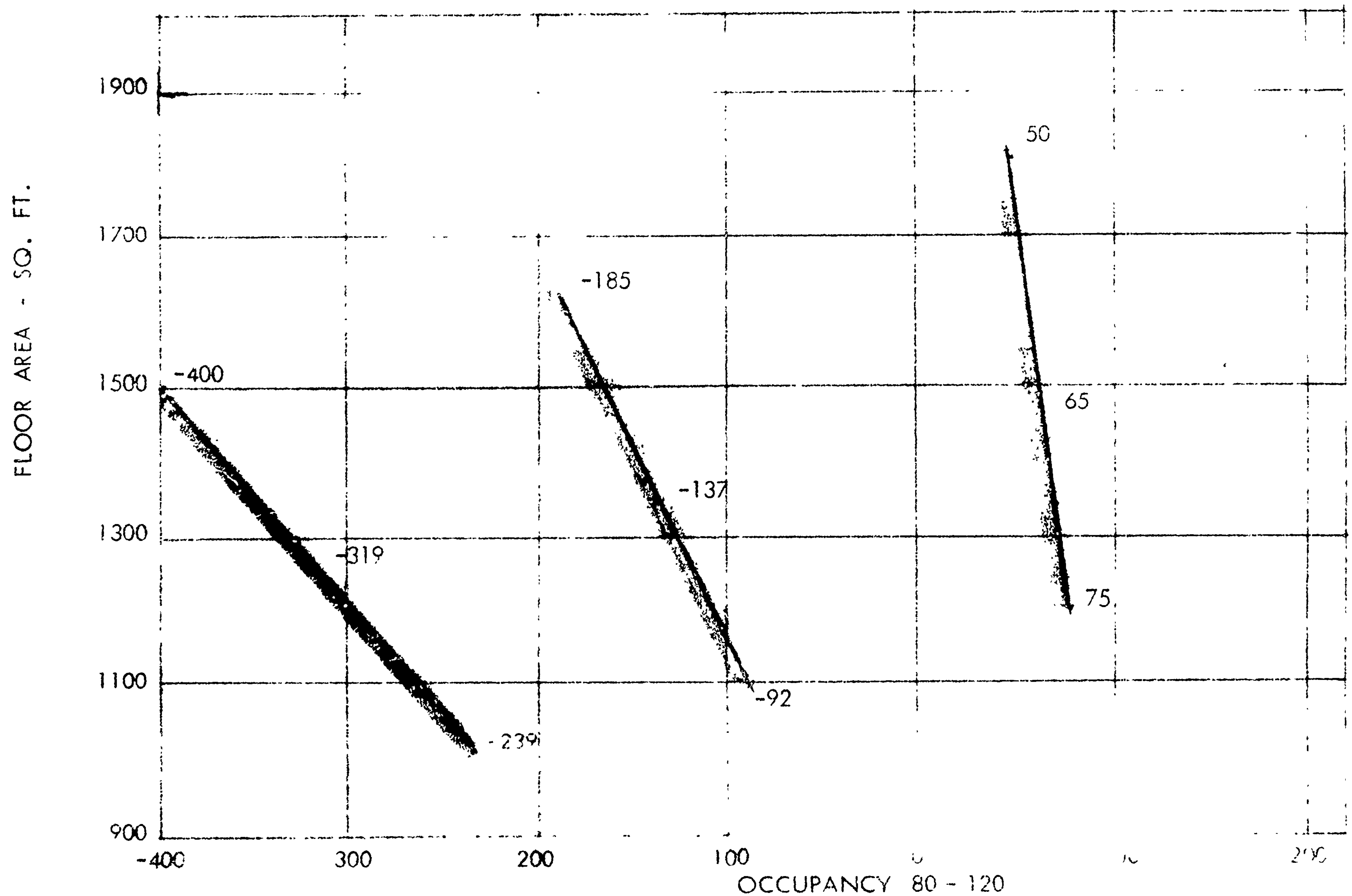


FIG. 2c

SQ. FT. OF ACOUSTICAL TILE REQ'D. - NRC .80
CARPETED FLOORS

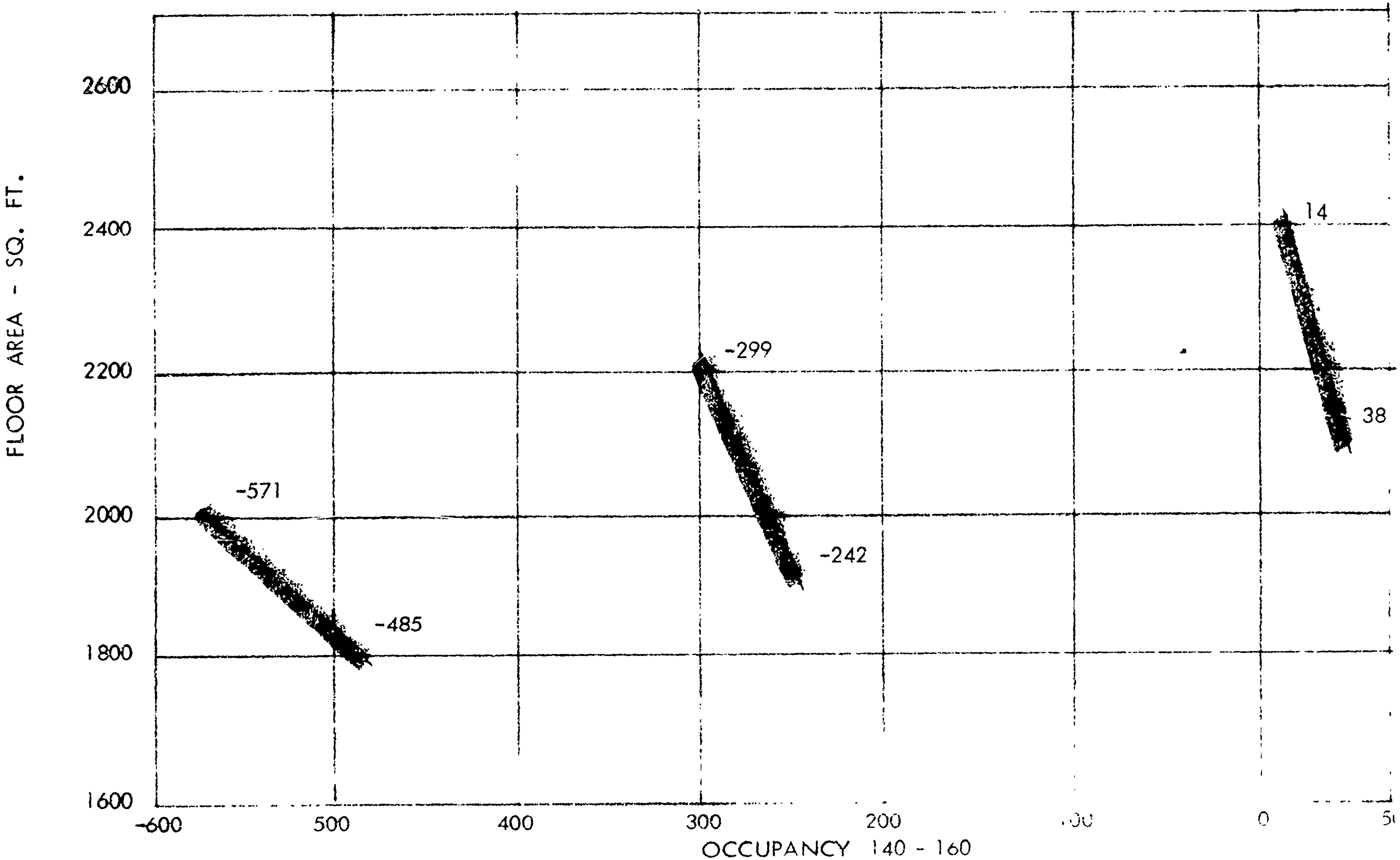


FIG. 2d

2 OF 2

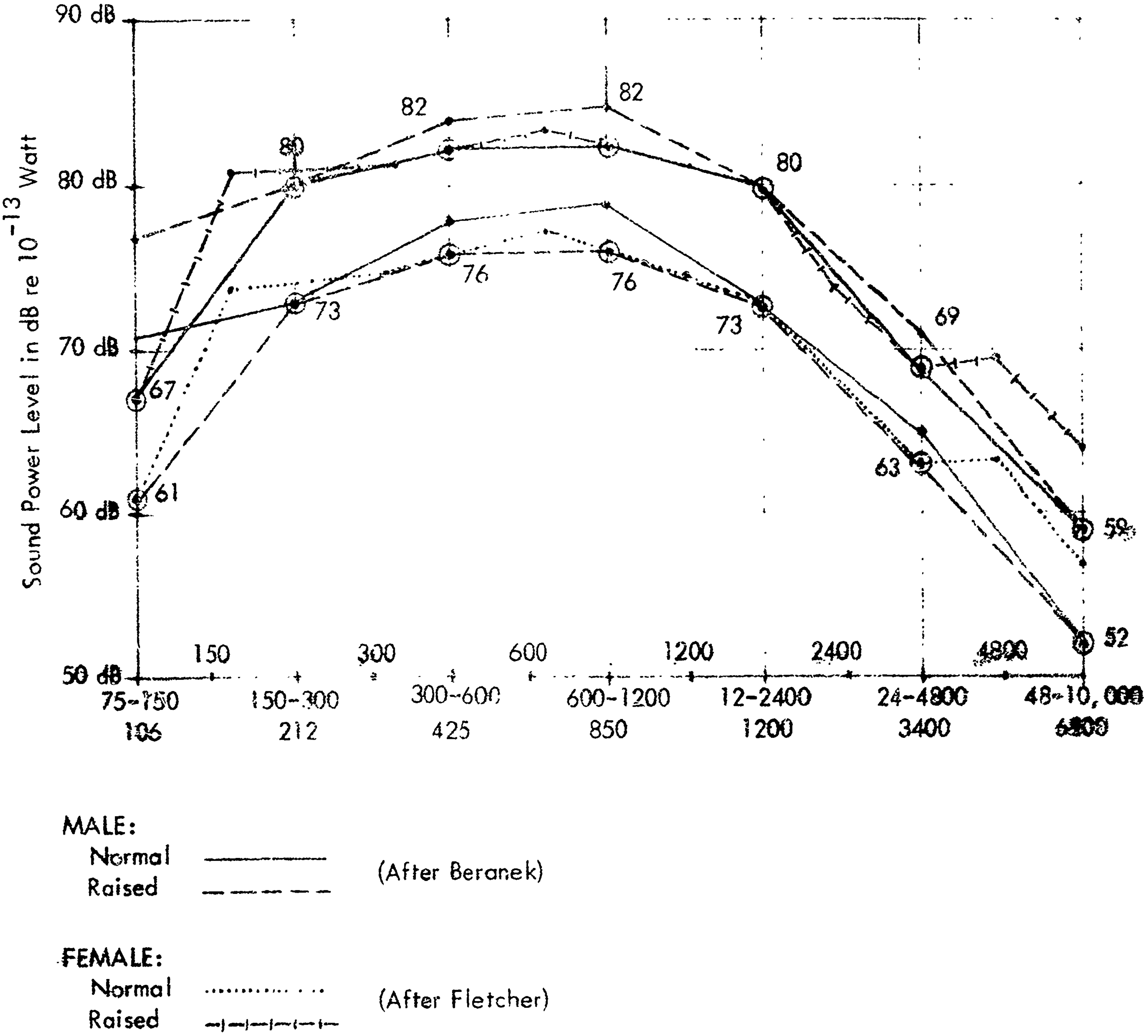
ED

1807

1.0 1.1 1.25 1.4 1.6 1.8 2.0 2.2 2.5 2.8 3.2 3.6 4.0 4.5 5.0 5.6 6.3

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963

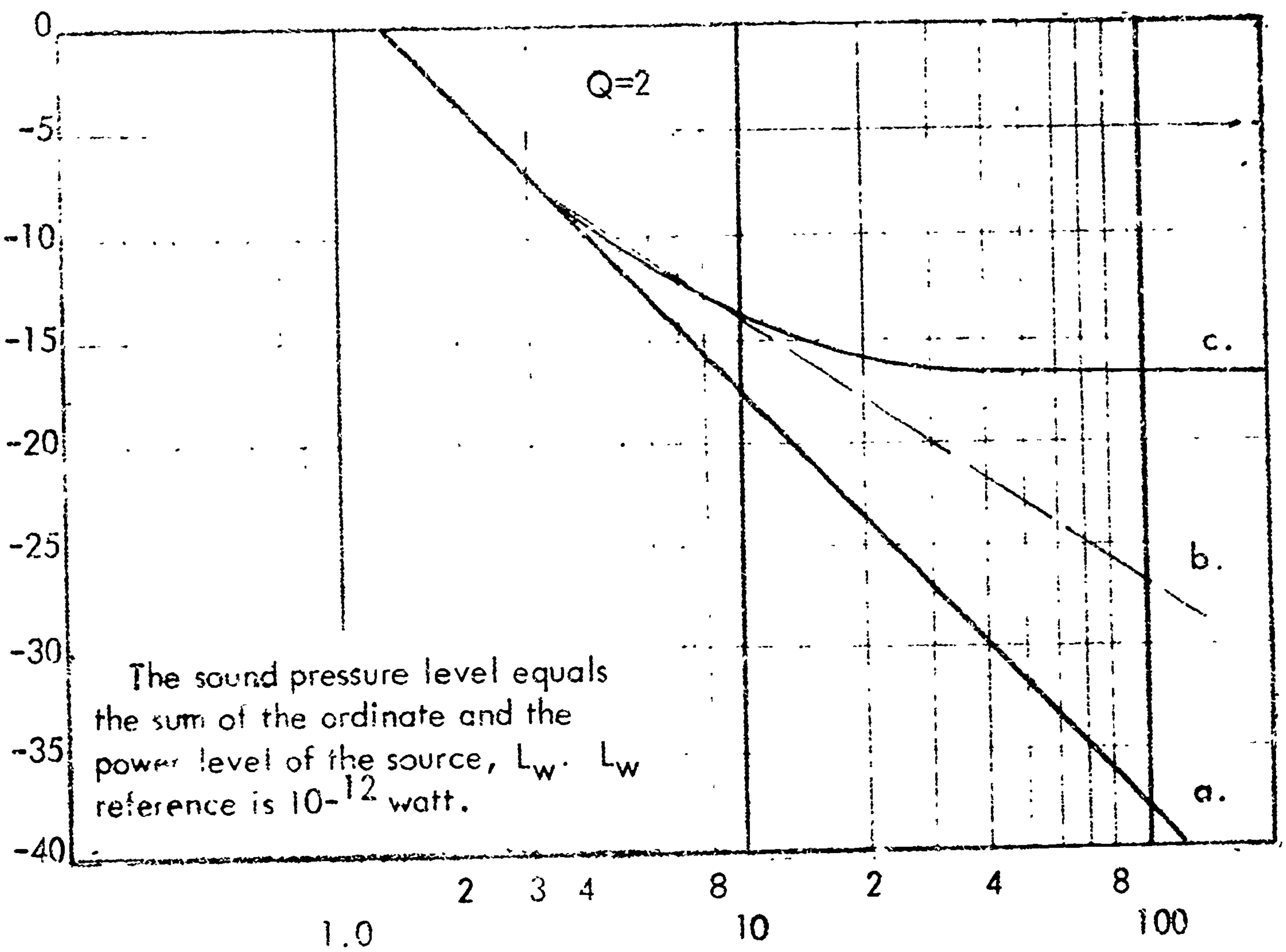


OCTAVE BAND POWER LEVELS - HUMAN VOICE

FIG. 3

Chart for determining sound pressure level in a room, produced

by a directional sound source



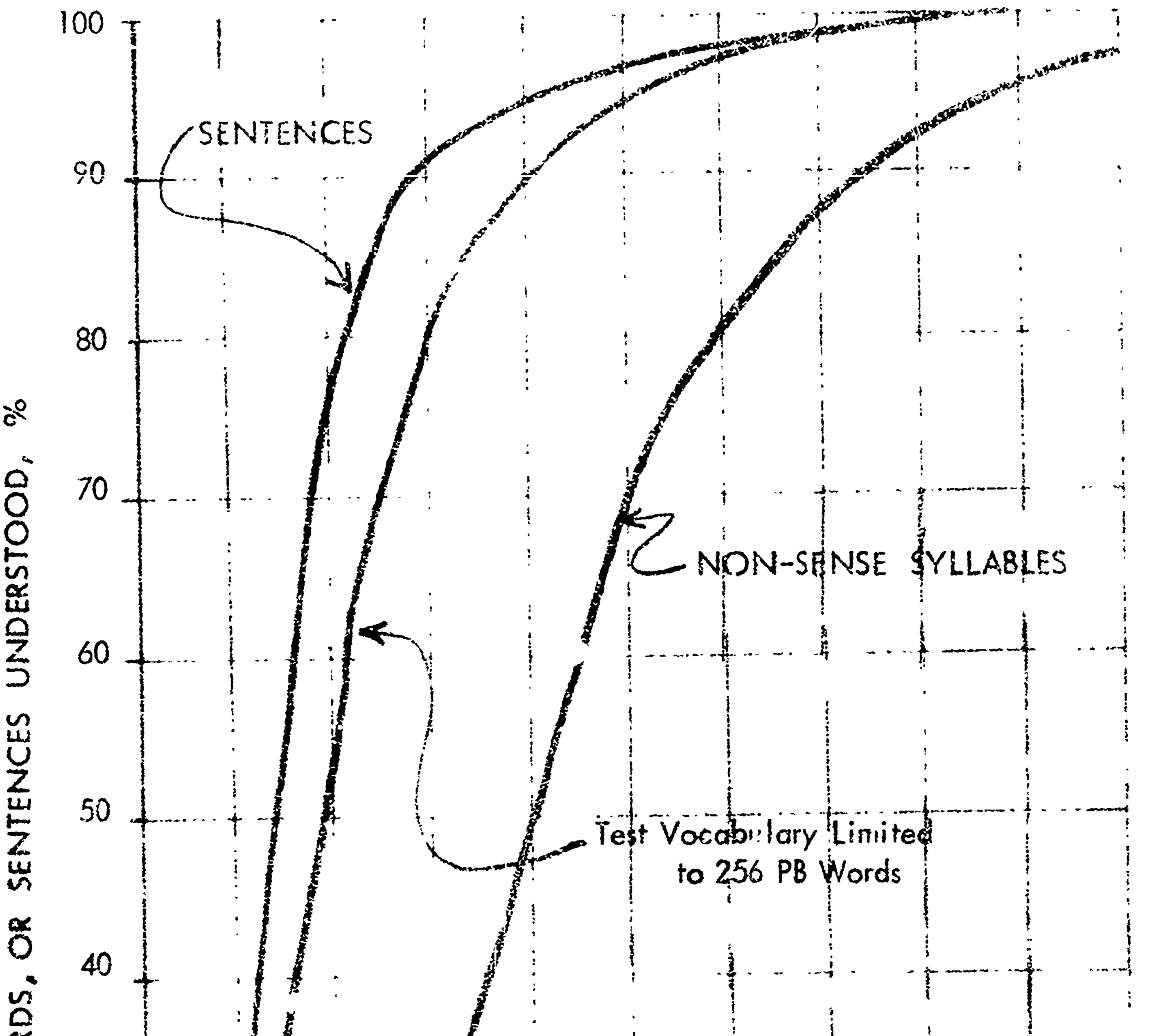
Distance in Feet

Curve a– Uniform reduction in SPL with distance, at 6 dB/doubling of distance

Curve b– Uniform reduction in SPL with distance, at 4.5 dB/doubling of distance

Curve c– Statistical preduction of SPL reduction with distance, for a room constant, R, of 700

Figure 4



SYLLABLES, WORDS, OR SENTENCES UNDERSTOOD, %
100
90
80
70
60
50
40
30
20
10
0
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
ARTICULATION INDEX
SENTENCES
NON-SENSE SYLLABLES
Test Vocabulary Limited to 256 PB Words

FIG. 5

ACCEPTABLE NC LEVELS
NORMAL VOICE

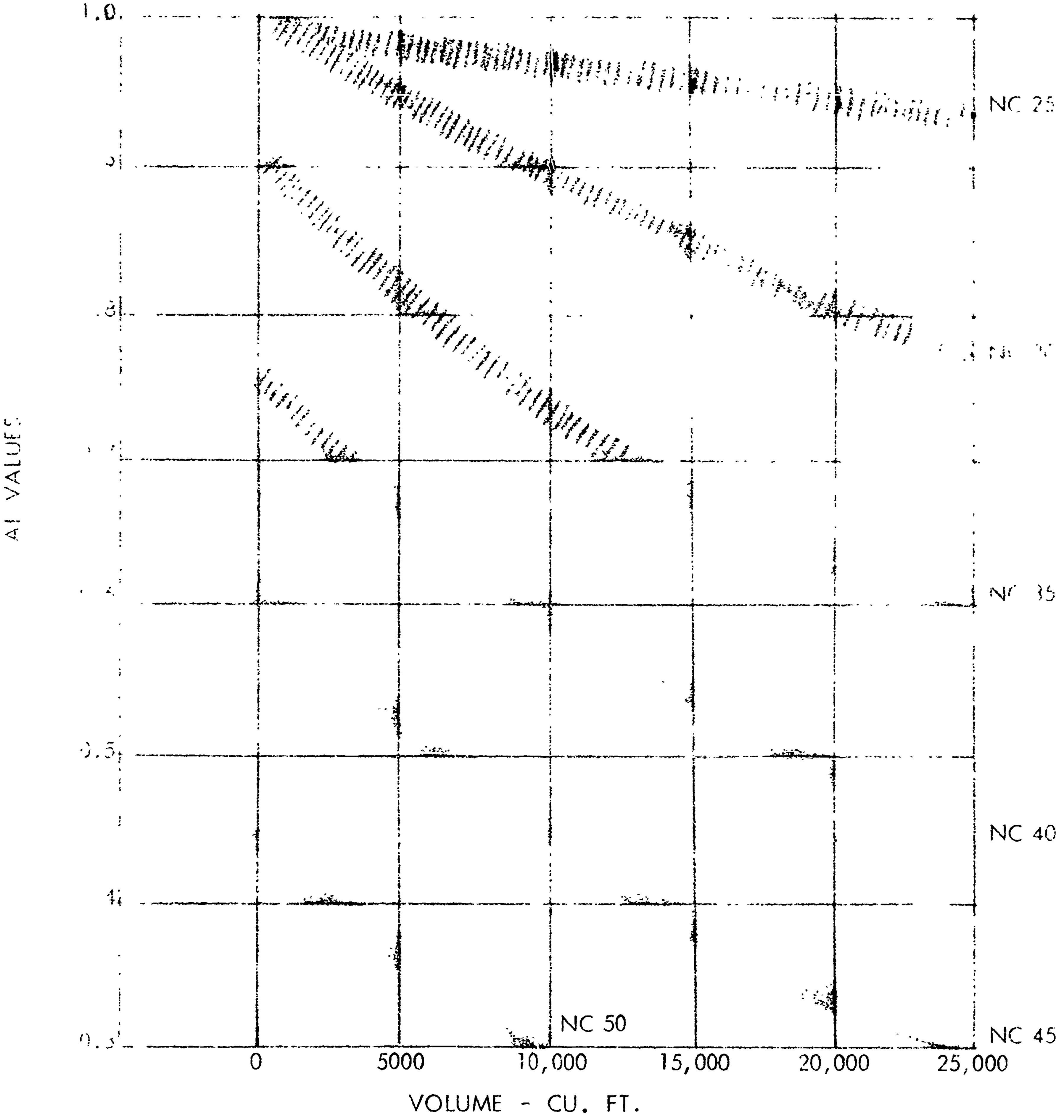
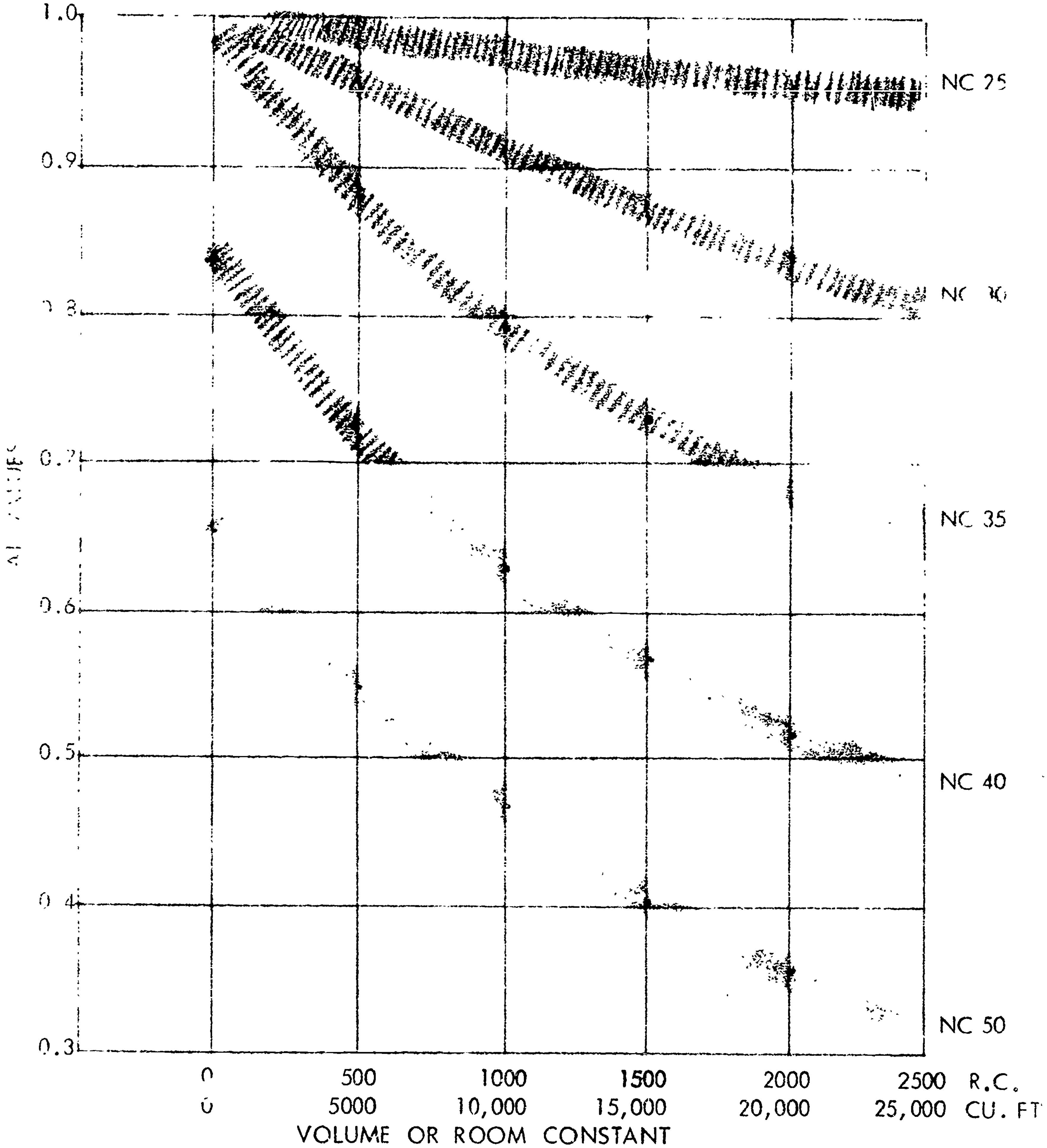


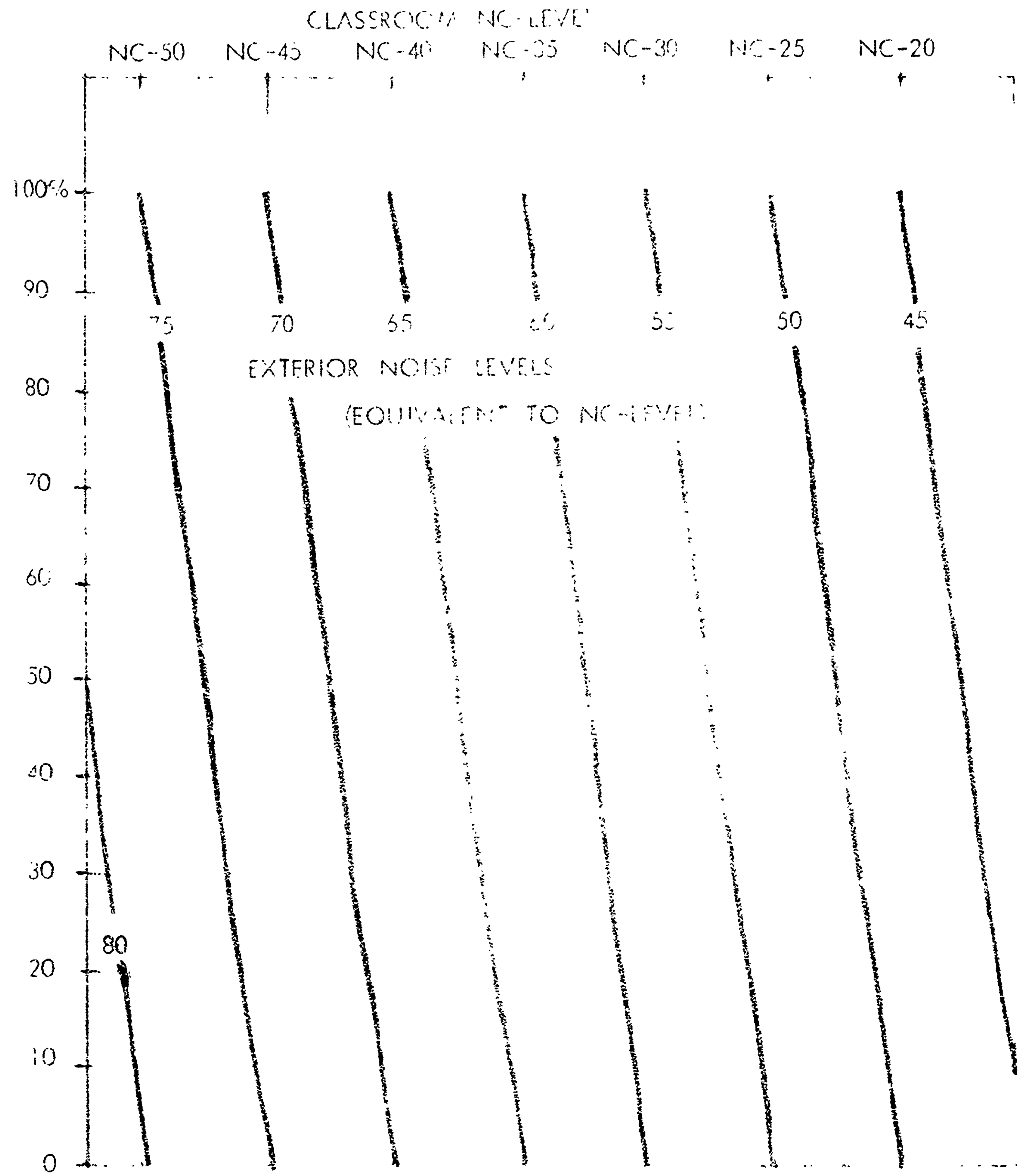
FIG. 6a

ACCEPTABLE NC LEVELS
RAISED VOICE



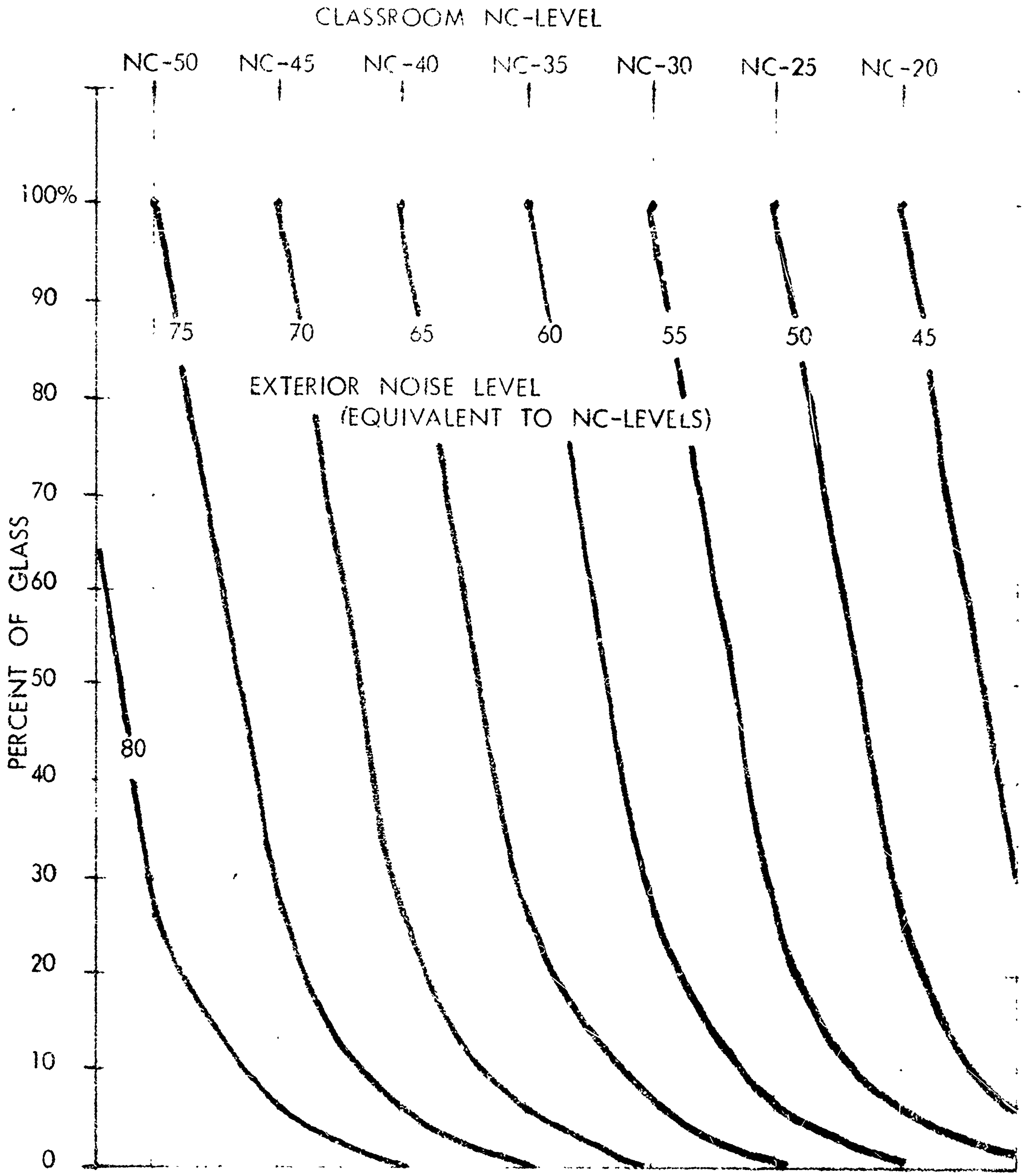
Low Reverb. Time -'R' Tends to Move to Right.
High Reverb Time - 'R' Tends to Move to Left.

FIG. 4



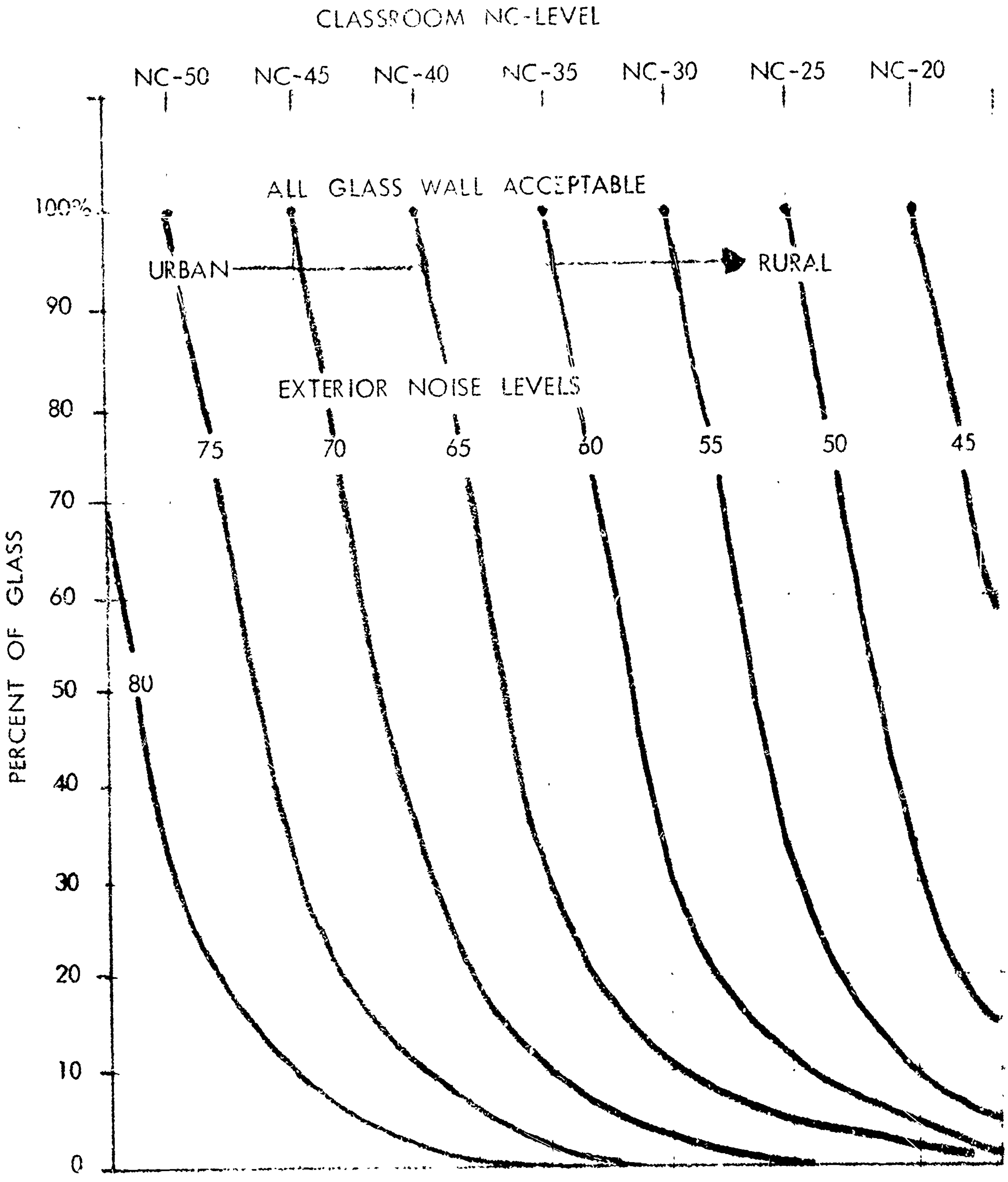
Acceptable Percentage of Glass
in a Typical Exterior Wall
of TL-30

FIG - A



Acceptable Percentage of Glass
in a Typical Exterior Wall
of TL-40

FIG. 7-B



Percentage of Acceptable Glass Area in a Brick & Block Exterior Wall (TL-55), for Varying Exterior Noise Levels

FIG. 7-C

AI BETWEEN CLASSROOMS FOR
DIFFERENT STC'S & NC'S

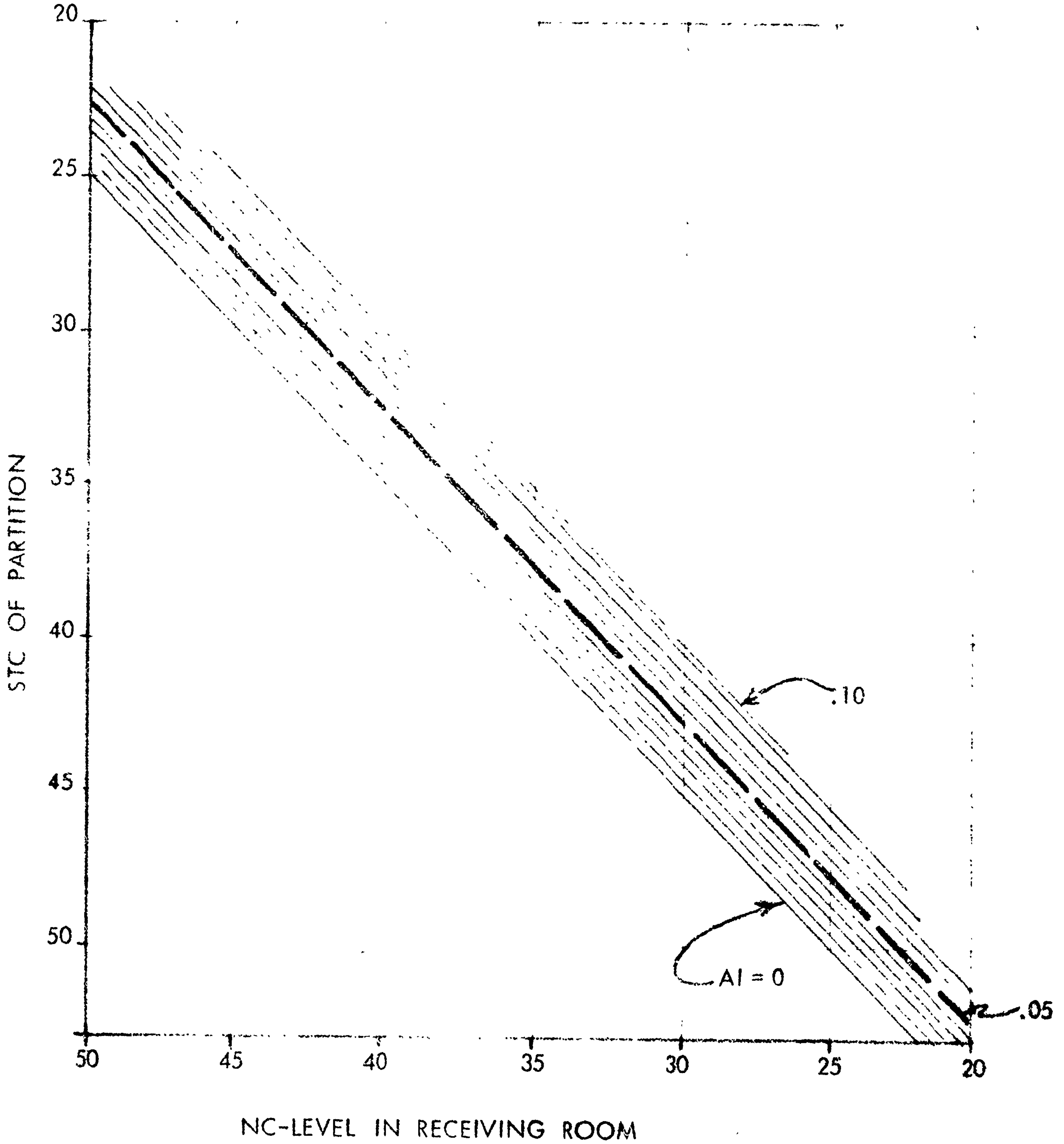


FIG. 8

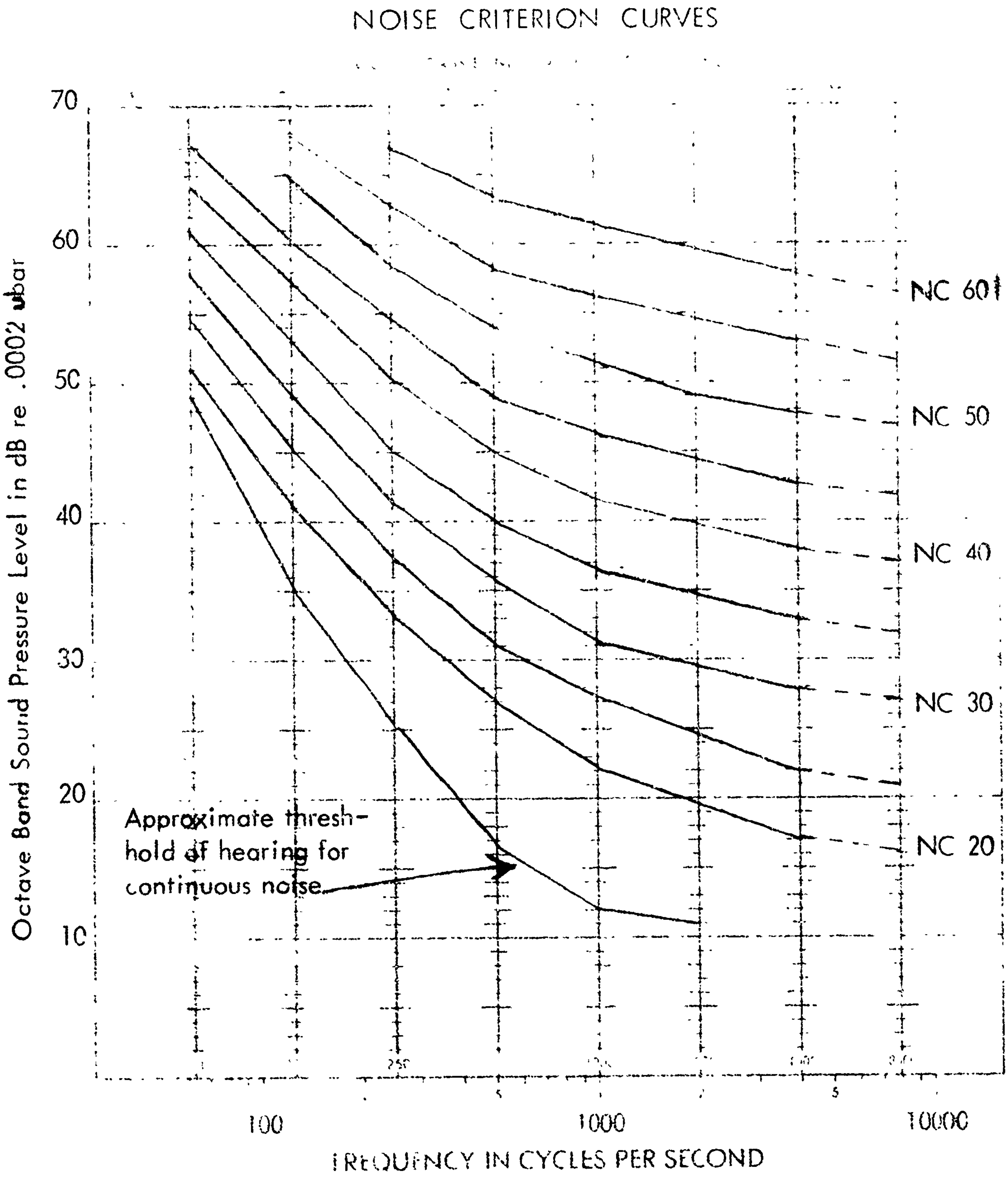

NOISE CRITERION CURVES
70
60
50
40
30
20
10
Octave Band Sound Pressure Level in dB re .0002 µbar
NC 60
NC 50
NC 40
NC 30
NC 20
Approximate thresh-
hold of hearing for
continuous noise.
100
1000
10000
FREQUENCY IN CYCLES PER SECOND

Figure 9

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TITLE

Design Guidelines for Good Hearing Conditions and Effective Noise Control in School Classrooms

AUTHORS

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PAGINATION

RETRIEVAL TERMS

Classrooms
Classroom Noise
Reverberation Time
Speech Perception
Articulation Index
Speech Articulation
Acoustical Guidelines

IDENTIFIERS

ABSTRACT

Two of the most important operative design factors governing speech perception in classrooms have been examined and guidelines in the form of graphs, etc. constructed that should be understandable to and usable by those associated with school planning and design. The two factors considered are: 1) provision for optimum reverberation time, and 2) prediction of speech intelligibility (articulation) by use of the Articulation Index. The required additional acoustic absorption to provide optimum reverberation times in a variety of classroom sizes and occupancies is shown in the form of graphs. Articulation Index is a weighted fraction representing, for given speech and noise conditions the effective proportion of the normal speech signal available to the listener for conveying speech intelligibility. Considered in the calculations are the nature of the speech spectrum, attenuation of the speech signal before reaching the ear and the effects of noise in masking the signal. Starting with known facts, and assumptions, noise level limits for effective speech communication are determined for various speaker-listener distances typical of classrooms. Using these calculated values, guideline graphs have been prepared which show what sound transmission loss properties of exterior and interior walls are required, for several exterior noise conditions, to meet the calculated noise level limits. Selection of classroom heating and ventilating equipment to meet these calculated maximum noise levels is also considered.